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Investigation of a Rotor System Incorporating a Constant-Lift Tip

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M.A. McVeigh
H. Rosenstein
K. Bartie
F.J. McHugh

Boeing Vertol Compnay

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M.A. McVeigh
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Boeing Vertol Compnay
P.O. Box 16858
Philadelphia, Pennsylvania 19142

Prepared for
Ames Research Center
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M.A. McVeigh, H. Rosenstein, K. Bartie, and F.J. McHugh

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16 Abstract

A wind tunnel test of a 16.8 ft. model of a rotor having passively controlled pivotable tips is described. Performance and vibratory hub load data are presented which compare the performance of the rotor with the tips free and fixed. A brief analysis of the experimental findings is included.

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FOREWORD

The work reported in this document was performed by the Boeing Vertol Company for the National Aeronautics and Space Administration - Ames Research Center under Contract NAS2-10769 during the period December 1980 through October 1981.

The NASA Technical Monitor was Mr. Robert H. Stroub, and the Boeing Program Manager was Mr. Harold Rosenstein. The Boeing Project Engineer was Mr. Michael A. McVeigh.

ABSTRACT

A wind tunnel test of a 16.8 foot model of a rotor having passively-controlled pivotable tips is described. Performance and vibratory hub loads data are presented, which compare the performance of the rotor with the tips free and fixed. A brief analysis of the experimental findings is included.

SUMMARY

A wind tunnel test of a 16.8 foot diameter model of a free tip rotor is described. The test was conducted at full-scale tip speeds up to an advance ratio of 0.4. Measurements were made of the rotor vibratory hub loads and performance, both with the tips free to operate and with them locked. It was found that the 4/rev vibratory resultant in-plane loads were reduced when the tips were free, but that power required and the vertical 4/rev loads were greater than with the tips locked. Analysis of the data showed that the reduced performance was attributable to the free tip operating at angles of attack well beyond the anticipated value. This resulted in excessive tip drag and increased power.

Detailed performance data and cross plots of this data are presented in appendices.

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1.0 INTRODUCTION

1.1 Basic Concept

The constant-lift tip rotor concept uses a blade tip segment that is passively controlled in pitch in such a way that each tip operates at essentially constant lift as the blade moves around the azimuth. The principle of operation is illustrated by Figure 1.1 which shows a rotor blade whose tip is free to rotate about a pivot.

In order for the tip to operate at essentially constant lift, it is pivoted ahead of its own aerodynamic center, with the blade balanced so that the c.g. lies on the pivot. If a nose-up controlling moment is now supplied to the tip via the pivot, the tip develops positive lift and a nose-down pitching moment that grows until the pivot-supplied moment is cancelled. By designing the pivot mechanism to supply a moment that is constant (independent of azimuth and tip deflection), then the tip is forced to fly at constant lift.

The freedom to rotate ensures that the inboard blade will be isolated from the tip torsional loads. If the tip were so designed that it would operate at a prescribed lift level independent of azimuth, then the tip-induced vertical and torsional vibratory loads would be eliminated. This could contribute significantly to the alleviation of helicopter vibration.

A further benefit of the constant lift feature is a potential improvement in rotor lift-to-effective drag ratio, L/D_e. On a conventional rotor the tip is negatively loaded on the advancing side while maintaining high positive lift on the retreating side. With the constant-lift (free tip) concept, the advancing side is positively loaded, which should improve L/D_e.

1.2 Analytical Studies

A theoretical evaluation of the constant-lift tip rotor is reported in Reference 1. The analysis used was V-7, a modified version of Boeing Vertol Program C-60. The math model incorporated the following features:

1. Blade element theory using airfoil lift, drag, and pitching moment tables that include stall and compressibility.

2. Unsteady aerodynamics effects.

3. Nonuniform downwash based on a prescribed wake.

4. Motion of the free tip obtained by solving tip equation of motion.

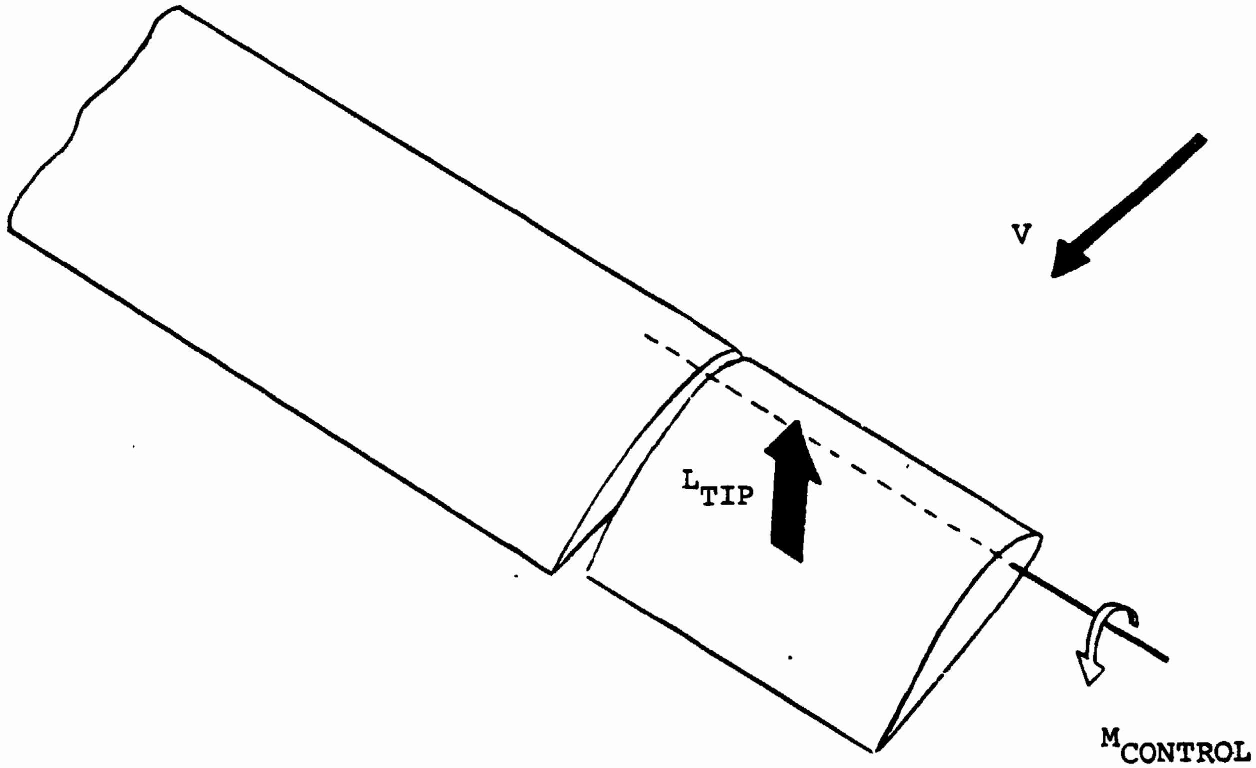

FIGURE 1.1. SCHEMATIC OF FREE-TIP CONCEPT

5. Fully-coupled flap/pitch motion of the blade with elastic flap and chord deflections and elastic torsion.

This program was applied to predict the performance of a hypothetical free-tip rotor having the following features:

Radius	=	25.5 feet
Chord	=	1.563 feet
Tip Span	=	18.36 inches (6% radius)
Pivot Location	=	13% chord
C.G. Location	=	13% chord
Tip Speed	=	704 ft/sec
Twist (Root-to-Tip)	=	-8° linear
No. of Blades	=	4

The performance was calculated with the tip fixed and free producing the same rotor lift and propulsive force, $C_T/\sigma = .073$, $\overline{X} = .108$. The results showed that the free tip required considerably less power than the conventional rotor. At 160 knots the savings was 11% and at 130 knots the percent gain was 24%.

1.3 Rotor Design

On the basis of this projected increase in aerodynamic performance, a feasibility study was made of a constant lift tip rotor system. The study was done in sufficient detail to identify the structural concept, method of attachment, and materials. The study was then extended to include the design, fabrication and test of a wind tunnel model of the free tip rotor having a 5% radius free tip. The design effort is reported in Reference (2). The wind tunnel test is described in this report.

2.0 MODEL DESCRIPTION

2.1 Free Tip

An existing four-bladed, 16-foot diameter, Mach-scaled model of the CH-47C rotor was selected for modification to the free tip design. This rotor had been previously modified to test a 4.8 inch (5% radius) tapered tip extension. The tapered tip extension was removed and a steel pitch shaft installed at 13% chord to carry the free tip (see Figure 2.1). The steel shaft had a helical groove cut into it. This groove accepted a cam follower pin which was inserted through the leading edge of the free tip. The pin was held in place by a retaining screw. This arrangement allowed the tip to pivot freely within the limits of the groove and still remain captured by the shaft. To minimize friction, the cam follower pin and groove were lubricated by a dry lubricant. Dry-lube bushings guided the pitching motion of the tip section. Provision was made to lock out the tip motion by removing the cam follower pins and replacing them with locking pins.

2.2 Tip Construction

The free tip had a V23010-1.58 airfoil with a 5.8 percent chord tab added to match the basic blade airfoil. The tip was constructed of Nomex core and magnesium spar covered with fiberglass. The upper surface had a 0.0005-inch thick Mylar cover to prevent air transfer from the lower to the upper surface. The spar was provided with one permanently-mounted 1/4-inch diameter tantalum balance weight in the nose and four 3/16-inch diameter holes symmetrically arranged about the pivot line. By inserting tantalum rods in these holes, the tip mass, inertia, and chordwise center-of-gravity could be varied. Table A-1 of Appendix A lists the values of these quantities.

2.3 Tip Instrumentation

The tip pitch shaft on one blade only was provided with flap and chord bending gauges as safety-of-flight instrumentation. The angle of the tip relative to the main blade was measured by a Hall-effect device. This device uses a remote magnetic field to modulate an electric current through a semi-conductor. The source magnet was placed in the moving tip and the sensor bonded to the main blade. The advantage of this method of measuring the tip angle is that there is no signal noise, or wiper pressure friction and wear associated with potentiometer arrangements. One slight disadvantage is the nonlinear (sinusoidal) output of the Hall device, which requires a nonlinear calibration algorithm in the data reduction process.

2.4 Main blade and Test Stand

The main blade was a 16-foot diameter model CH-47C rotor blade

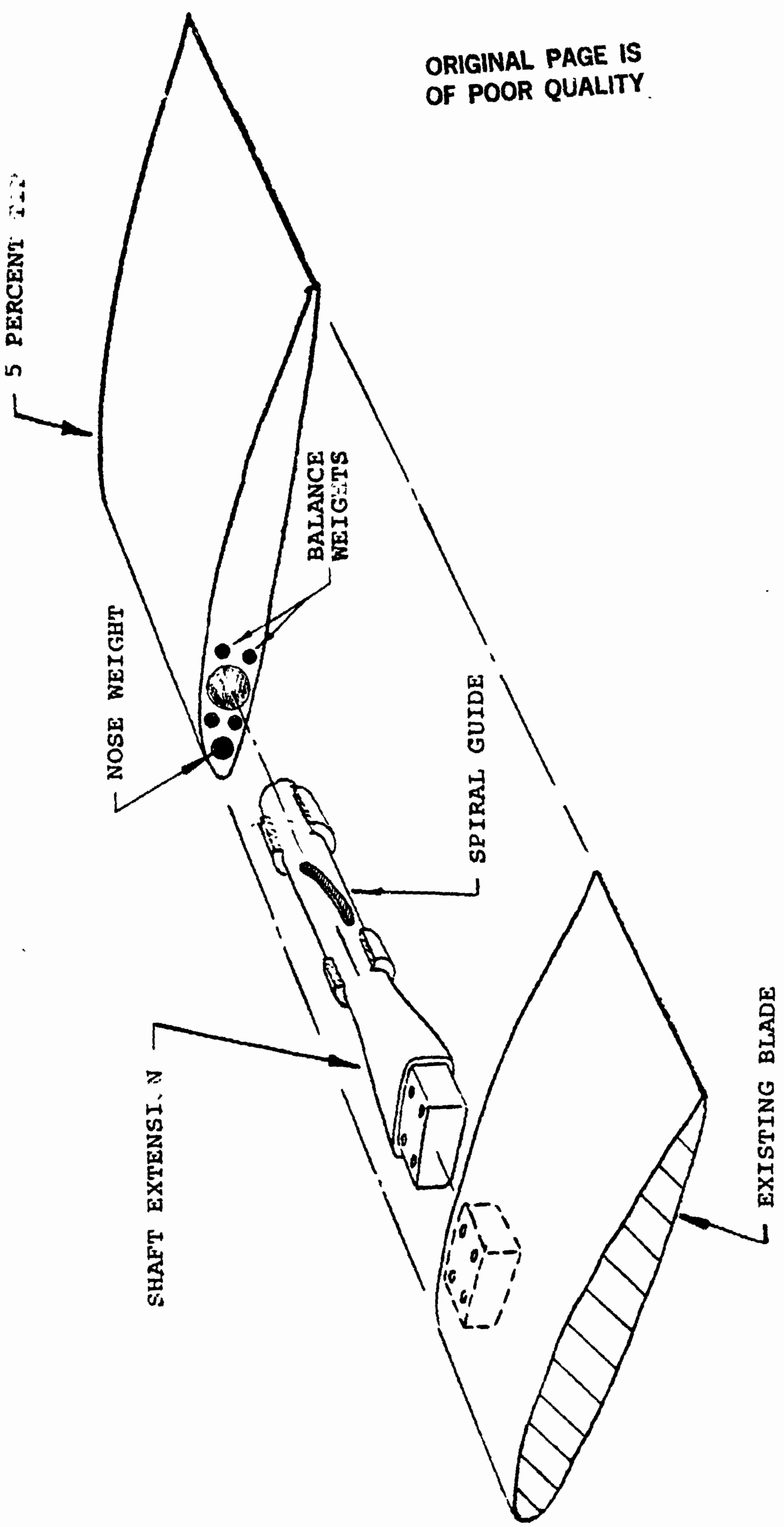

Figure 2.1 Constant Lift Tip Schematic

having a 6.73-inch chord, a constant V23010-1.58 airfoil, and -9 degrees of linear twist from center of rotation to the tip (r = 8'). The test stand was the Dynamic Rotor Test Stand (DRTS) which incorporates an electrical power supply and a 6-component balance. Figure 2.2 presents a photograph of the complete rotor with free tip and Figure 2.3 presents a close-up of one of the tips. The principal properties of the blade are summarized below.

Radius	8.4 ft.
No. of blades	4.0
Chord	6.73 inches (constant)
Solidity	0.085
Twist (center of rotation to tip)	-9.45 degrees
Airfoils	V23010-1.58 (constant)
Cutout	0.1825R
Flap Hinge	0.031R
Weight Moment about Flap Hinge	34.5 ft. lb
Inertia about Flap Hinge	4.55 slugs ft^2

Instrumentation for the main blade consisted of 6 flap bending gauges, 2 chord bending gauges and 1 torsion gauge placed as indicated in Table 2.1. Blade motion about the horizontal and vertical pins was continuously measured by transducers placed at the flap and lag hinges of the instrumented blade.

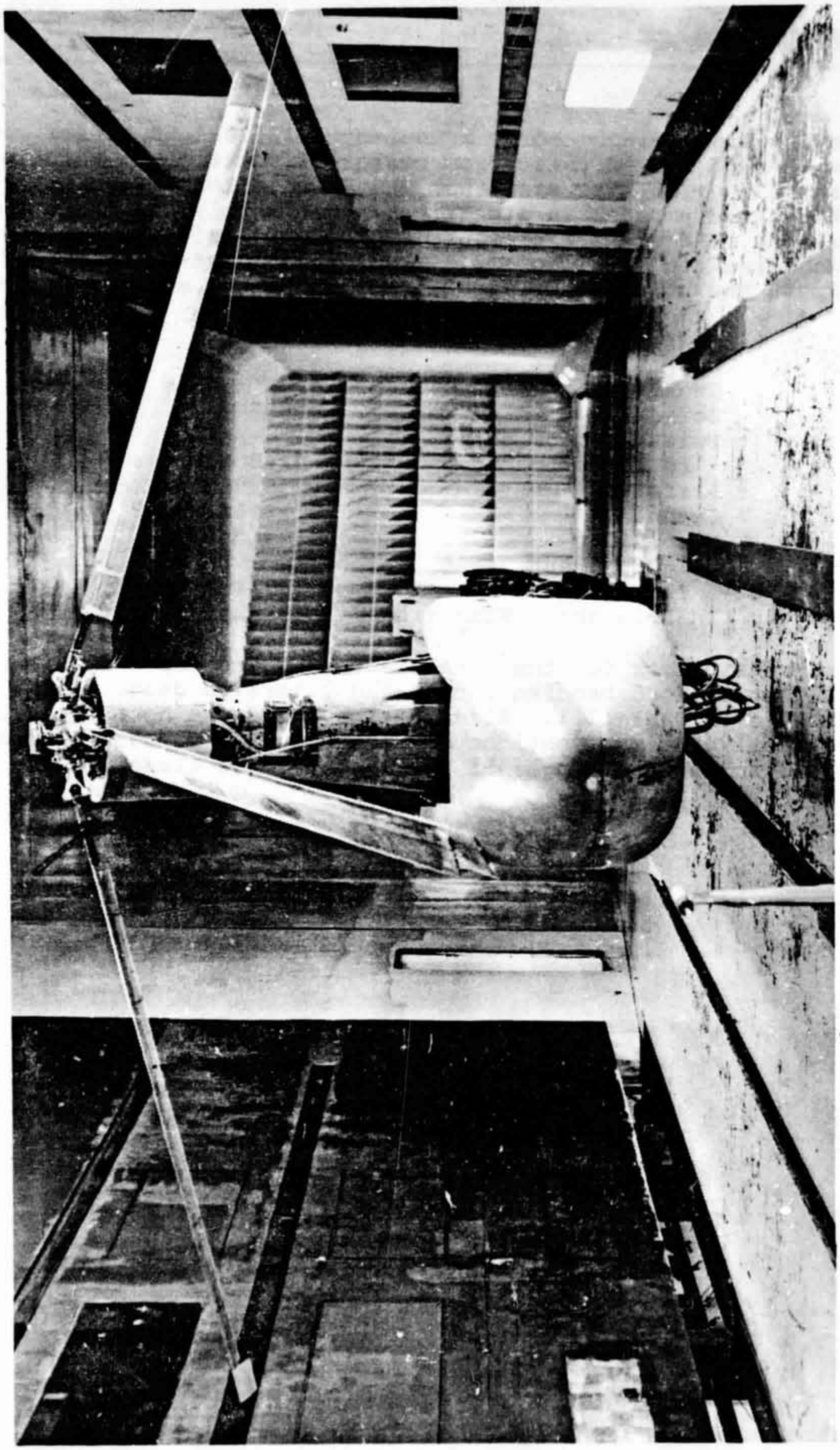

Figure 2.2 Model In Test Section

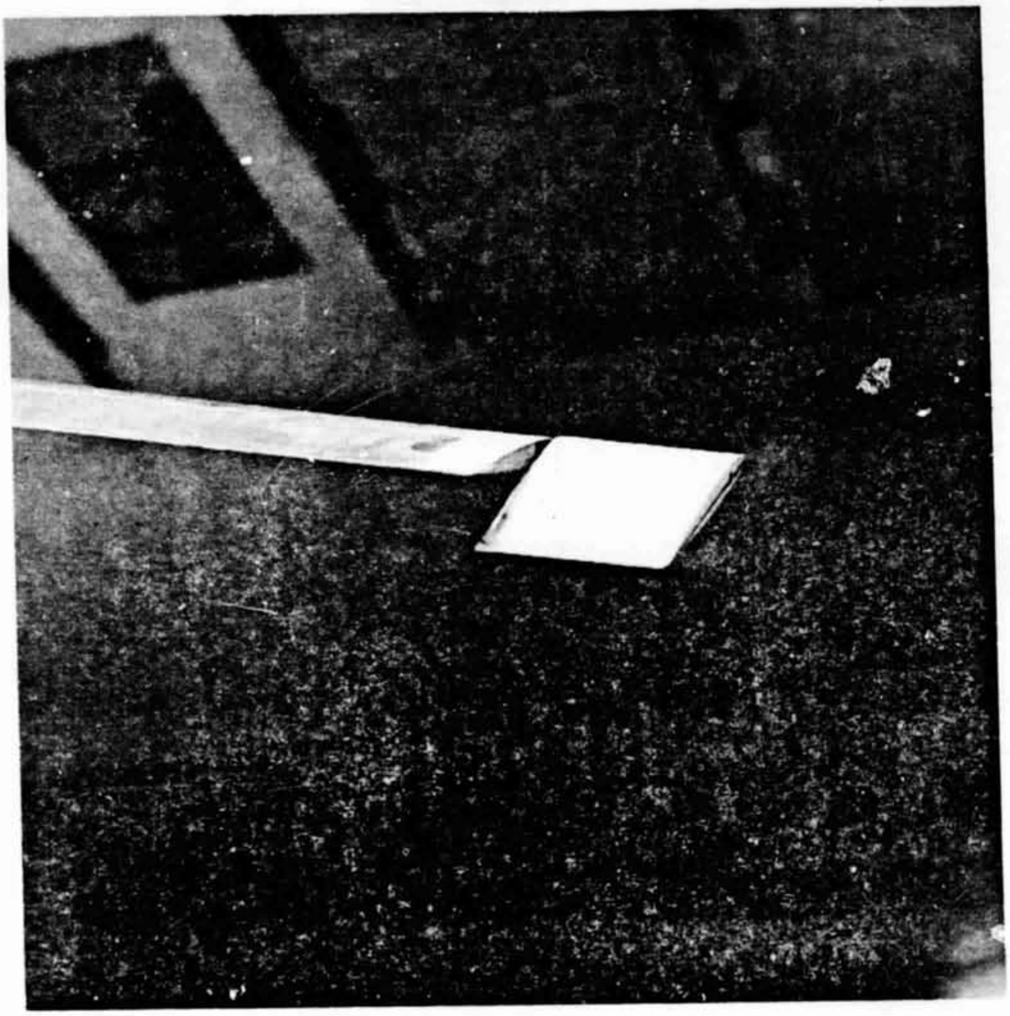

Figure 2.3 Free Tip

TABLE 2.1

LOCATION OF BLADE STRAIN GAUGES

GAUGE	BLADE STATION, % RADIUS
Flap Bending	12.6
	18.1
	38.4
	46.2
	53.3
	96.6
Chord Bending	18.1
	53.3
Torsion	12.6

3.0 DATA ACQUISITION

The wind tunnel test of a rotor requires the measurement of net rotor forces and moments, rotor control positions and blade loads almost simultaneously. To achieve this, the data is sensed, multiplexed, processed, then stored on magnetic tape and/or printed. Computed results in standard engineering units and coefficient format are tabulated by a line printer and selected variables are plotted by the X-Y plotters. Final data is stored on magnetic tape for additional processing.

A control panel digital display of nine channels of processed data is available for setting up model test conditions and monitoring purposes during the testing. Dynamic data of six quantities is continuously displayed on oscilloscopes to provide assistance in preventing model balance or rotor structural limits from being exceeded.

A data reduction program transforms the electrical signals and calculates the various tunnel parameters to be printed on-line. In addition to these items, the maximum and minimum values, mean value and alternating components of each selected blade load measurement are calculated and tabulated on-line.

Root flap bending, chord bending and torsion loads, as well as root flap and lag angle, are harmonically analyzed up to the first nine harmonics and the results are listed along with the other data. Following the test, waveforms are reconstituted from the dynamic data on the magnetic tapes.

At each test point, measurements are taken for computing and tabulating on-line the quantities listed. The listed balance forces and moments follow the sign convention illustrated in Figure 3.1.

(a) Tunnel and Model Parameters

Air density, ρ	slugs/ft^3
Freestream dynamic pressure, q	lb/ft^2
Tunnel velocity (corrected), V	ft/sec
Tunnel static temperature, T_s	°F
Rotor advance ratio, $\mu' = \frac{V}{\Omega R}$	-
Rotor collective angle, $\theta_{.75}$	deg
Rotor lateral cyclic angle, A_{1c}	deg

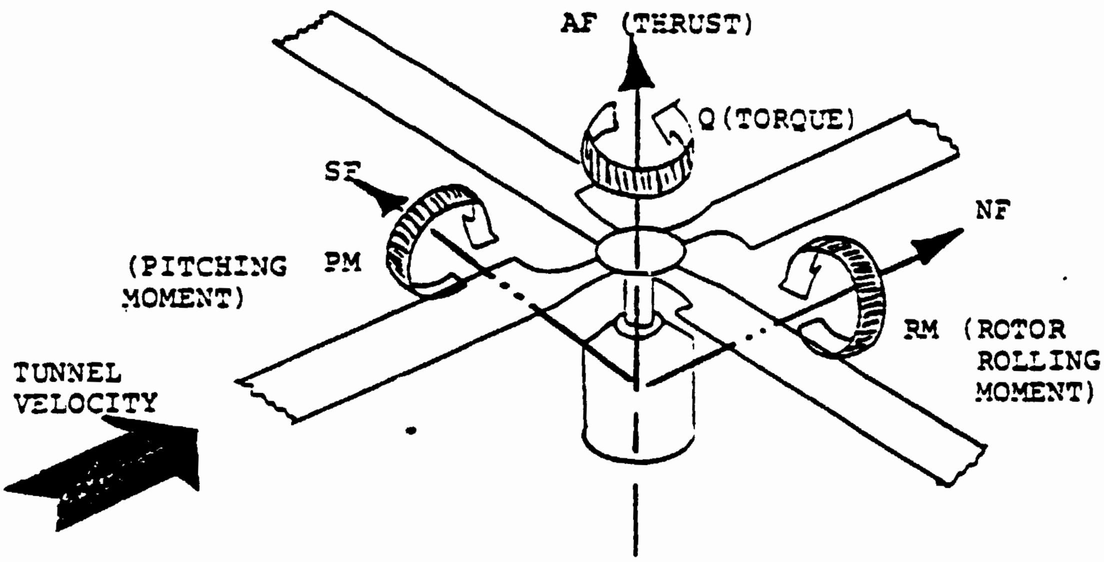

Figure 3.1 Force and Moment Sign Convention

(a) Tunnel and Model Parameters (continued)

Rotor longitudinal cyclic angle, B_{1c}	deg
Rotor rotational speed, Ω	RPM
Rotor shaft angle, α_s	deg
Blade flapping angle, β	deg
Blade lag angle, ζ	deg

(b) Total Loads Balance and Instrumented Shaft

Axial force (thrust), T	lb
Normal force, NF	lb
Side force, SF	lb
Pitching moment, PM	ft-lb
Yawing moment, YM	ft-lb
Shaft torque, Q	ft-lb

Forces and moments from the balances are printed on-line in engineering units as forces and moments with the wind-off zeros removed, with balance interaction corrections applied, and with the weight tares removed.

Corrected rotor balance forces and moments are reoriented into standard aircraft axes system and transferred on-line to the hub center so that moments could be evaluated in the plane of the rotor. The resolved shaft-axis system hub forces and moments are noted in the following list along with their sign convention.

Rotor Hub Forces/Moments (Shaft Axes)

Thrust, T (positive up)	lb
H force (positive aft)	lb
Side force (positive to the right)	lb
Hub pitching moment (positive nose up)	ft-lb
Hub rolling moment (positive advancing tip down)	ft-lb
Yawing moment (Q_f, friction torque)	ft-lb

Since the hub-generated forces and moments are included in the measured 'rotor' characteristics, it is necessary to establish hub tares and subtract them from the main rotor balance measurements. The hub tares are obtained from blade-off runs conducted at the normal operating speed. The rotor data is reduced on-line in coefficient form in the shaft axes system. Hub pitching moment, hub rolling moment and side force are retained in their more meaningful dimensional form.

Main rotor thrust coefficient, $C_T/\sigma = \dfrac{T}{\rho(\Omega R)^2 A\sigma}$
(where σ is the rotor solidity)

Main rotor power coefficient, $C_P/\sigma = \dfrac{Q}{\rho(\Omega R)^2 AR\sigma}$

Rotor data is also reduced on-line in the following engineering units and non-dimensional forms in the wind axes system. Hub side force components are included when the model is yawed.

$$D_e = \frac{\pi RPM}{30V}(Q-Q_f) - X$$

Lift to equivalent drag ratio, L/D_e

Rotor lift coefficient, $C'_T/\sigma = \dfrac{L}{\rho(\Omega R)^2 A\sigma}$

Propulsive force coefficient, $\dfrac{X}{qd^2\sigma}$ or $\overline{X}$

Figure 3.2 presents a sample printout.

SUMMARY LISTING
RUN 47 N0Z 47 NT 0

LOW SPEED CALCULATED DATA

RUN	TP	MU'	ALPHAS	RPM	VTIP	M1(90)	M1(270)
47	2	3.4999E-01	-1.7506E+00	7.9600E+02	7.0019E+02	8.2899E-01	3.9915E-01
	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	4	3.4978E-01	-1.5244E+00	7.9400E+02	6.9843E+02	8.2552E-01	3.9760E-01
	5	3.4957E-01	-1.4552E+00	7.9600E+02	7.0019E+02	8.2723E-01	3.9659E-01
	6	3.5003E-01	-1.3830E+00	7.9400E+02	6.9843E+02	8.2510E-01	3.9725E-01
	7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	8	3.5022E-01	-4.7156E+00	7.9600E+02	7.0019E+02	8.2642E-01	3.9771E-01
	9	3.5032E-01	-4.5974E+00	7.9600E+02	7.0019E+02	8.2625E-01	3.9754E-01
	10	3.5055E-01	-4.4558E+00	7.9400E+02	6.9643E+02	8.2610E-01	3.9629E-01
	11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	12	3.4576E-01	-4.3545E+00	7.9400E+02	6.9843E+02	8.2320E-01	3.9657E-01
	13	3.5073E-01	-8.6457E+00	7.9600E+02	7.0019E+02	8.2559E-01	3.9684E-01
	14	3.5064E-01	-8.5473E+00	7.9600E+02	7.0019E+02	8.2530E-01	3.9679E-01
	15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	16	0.0000E+00	1.6917E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

RUN	TP	VTUN	QTUN	RHOTUN	CTB	CTR	CHB
47	2	2.4506E+02	6.6031E+01	2.1990E-03	3.4391E-03	3.[illegible]300E-03	2.3022E-04
	3	2.4540E+02	6.6115E+01	2.1956E-03	5.1420E-03	5.1430E-03	[illegible].3911E-04
	4	2.4430E+02	6.5441E+01	2.1431E-03	6.8204E-03	6.8[illegible]5E-03	2.0792E-04
	5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	6	2.4447E+02	6.5441E+01	2.1699E-03	8.4726E-03	8.4741E-03	1.4036E-04
	7	2.4422E+02	6.5256E+01	2.1681E-03	9.0714E-03	9.0727E-03	1.0013E-04
	8	2.4522E+02	6.5594E+01	2.1850E-03	3.4454E-03	3.4423E-03	2.3581E-04
	9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	10	2.4484E+02	6.5424E+01	2.1528E-03	6.8340E-03	6.8273E-03	2.0360E-04
	11	2.4454E+02	6.5239E+01	2.1019E-03	7.7098E-03	7.7171E-03	1.9276E-04
	12	2.4426E+02	6.5071E+01	2.1009E-03	8.4370E-03	8.4340E-03	1.5764E-04
	13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	14	2.4552E+02	6.5626E+01	2.1774E-03	5.0589E-03	5.0490E-03	2.3149E-04
	15	2.4613E+02	6.5090E+01	2.1755E-03	5.4321E-03	6.4229E-03	2.3464E-04
	16	0.0000E+00	0.0000E+00	2.2460E-03	0.0000E+00	0.0000E+00	0.0000E+00

RUN	TP	CHR	CYB	CYR	CPB	CPR	CT'B
47	2	3.7305E-04	-5.5395E-05	-5.5200E-05	2.9090E-04	2.9512E-04	3.4447E-03
	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	4	3.4383E-04	-1.9431E-04	-1.9387E-04	4.1321E-04	4.1715E-04	6.0235E-03
	5	3.2060E-04	-2.0535E-04	-2.0519E-04	4.6152E-04	4.6506E-04	7.5092E-03
	6	2.6399E-04	-2.4995E-04	-2.4691E-04	5.3097E-04	5.4312E-04	8.0739E-03
	7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	8	3.8163E-04	-4.9307E-05	-4.9532E-05	3.5003E-04	3.5421E-04	3.4531E-03
	9	3.6076E-04	-9.8407E-05	-9.8623E-05	4.3480E-04	4.3904E-04	5.1344E-03
	10	3.5126E-04	-1.8720E-04	-1.8740E-04	5.5036E-04	5.5454E-04	6.8254E-03
	11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	12	3.0211E-04	-2.5806E-04	-2.5865E-04	7.0556E-04	7.0975E-04	8.4240E-03
	13	4.0012E-04	-2.0579E-05	-2.0857E-05	4.4135E-04	4.4557E-04	3.4076E-03
	14	3.8009E-04	-8.4312E-05	-8.4594E-05	5.7093E-04	5.7510E-04	5.0372E-03
	15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	16	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

RUN	TP	CT'R	CXB	CXR	CDEB	CDER	L/QD2A
47	2	3.4497E-03	-1.3125E-04	-2.6774E-04	9.6239E-04	1.1110E-03	4.4172E-02
	3	5.1516E-03	-9.2355E-05	-2.2976E-04	1.0440E-03	1.1933E-03	6.5488E-02
	4	6.0283E-03	-2.6400E-05	-1.6223E-04	1.2072E-03	1.3549E-03	8.7009E-02
	5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	6	8.4785E-03	5.0170E-05	-7.9308E-05	1.4030E-03	1.6310E-03	1.0064E-01
	7	9.0757E-03	1.1154E-04	-2.3500E-05	1.0307E-03	1.7057E-03	1.1054E-01
	8	3.4620E-03	4.5231E-05	-9.7345E-05	9.0123E-04	1.1087E-03	4.4224E-02
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	10	6.8340E-03	3.2534E-04	1.8021E-04	1.2400E-03	1.4017E-03	8.7247E-02
	11	7.7103E-03	3.9600E-04	2.5512E-04	1.3010E-03	1.5190E-03	9.[illegible]E-02
	12	8.4330E-03	4.8040E-04	3.3915E-04	1.5330E-03	1.6001E-03	1.[illegible]E-01
	13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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	15	6.4100E-03	7.1101E-04	5.5076E-04	1.2415E-03	1.4200E-03	8.1320E-02
	16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Figure 3.2 Sample Printout

4.0 TEST PROCEDURE AND CONDITIONS

4.1 Test Cell Checkout

4.1.1 Check on Tip Freedom of Movement

Before installing the rotor in the wind tunnel, the model was first checked for satisfactory operation and for freedom of movement of the tip. The check runs were made in the model test cell at gradually increasing tip speeds up to the normal operating speed of 700 ft/sec. At each speed a jet of compressed air was used to excite motion in the free tip and the response was observed. At low tip speed, the tip showed a highly damped response such as that presented in Figure 4.0a. At the operating tip speed no noticeable response was obtained; this is attributed to insufficient impulse being imparted by the air jets at the high tip speeds.

4.1.2 Determination of Controller Friction

Before actual wind tunnel testing was begun, a check was made of the friction forces acting on the pivot mechanism with simulated centripetal and lift loads applied to the tip. Various spanwise loads (to simulate C_F) were applied at the tip, co-linear with the main spar. The internal friction of the tip pivot mechanism was measured as a function of the resultant torque on the tip. The torque was measured using a simple cantilever beam attached to the tip, and a load cell attached between the end of the beam and ground.

Three separate types of loading were applied to the tip. A pure spanwise load applied in incremental units to simulate C_F load, a combined load by applying a load in the spanwise direction at an angle to the main spar axis. A pure spanwise load was applied along with a load orthogonal to the main spar axis (to simulate a pure lift load). This final loading was performed to find the component of lift affecting the measurement of torque through the load-link. The test set-up is shown in Figure 4.0b.

Although there was some hysteresis present in the measurement, the test showed that the friction level was acceptable and slightly lower than the expected value.

The rotor and test stand was then removed from the test cell and installed in the Wind Tunnel. Each rotor tip configuration was tested using the following procedure.

4.2 Track and Balance

The rotor was run up to operating rpm and the blades tracked and

balanced. Balance was declared acceptable if the resultant in-plane force was less than 10 pounds.

4.3 Hover

Floor and ceiling were removed and rpm sweeps were made in hover, holding rotor thrust coefficient, C_T, constant. Following the rpm sweeps the rpm was set to give the required tip speed, and the collective varied from -4° in increments of 1° up to the maximum achievable. This run was then repeated. In this way, excellent definition of the C_P vs. C_T curve was achieved. A high degree of definition is required in order to produce an adequate definition of rotor figure of merit.

4.4 Forward Flight

When the hover testing was complete the tunnel working section floor and ceiling were replaced ready for testing in forward flight. All testing was conducted with slotted floor, ceiling, and side walls.

At selected values of advance ratio (usually 0.2, 0.3, 0.35, 0.4) a thrust sweep at fixed shaft angle was made. Collective was increased until limited by power, cyclic control available, blade loads, or balance loads. The rotor was trimmed to give zero one-per-rev flapping.

Tip speed sweeps at fixed advance ratio (μ = .40) were made by varying rpm while tunnel speed was adjusted to give the advance ratio. A constant value of C_T and $\bar{X}$ was maintained and the rotor trimmed to zero 1/rev flapping.

4.5 Hub Tares

In isolated rotor tests, the hubs, pitch arms, pitch housings, and attachments are not normally representative of the full scale rotor system and those differences must be accounted for aerodynamically. The contributions from the model blade pitch arms, housings, and hub were established by testing with the blades removed. The tests covered the entire range of advance ratios, shaft angles, and control settings likely to be used during the test. The values of the hub tares were then subtracted from the measured rotor forces to give the blades-only forces.

4.6 Run Log

A copy of the Wind Tunnel test engineer's Run Log is presented in Figure 4.1. The nomenclature and flag notes used in the Run Log are defined in Figures 4.2 and 4.3.

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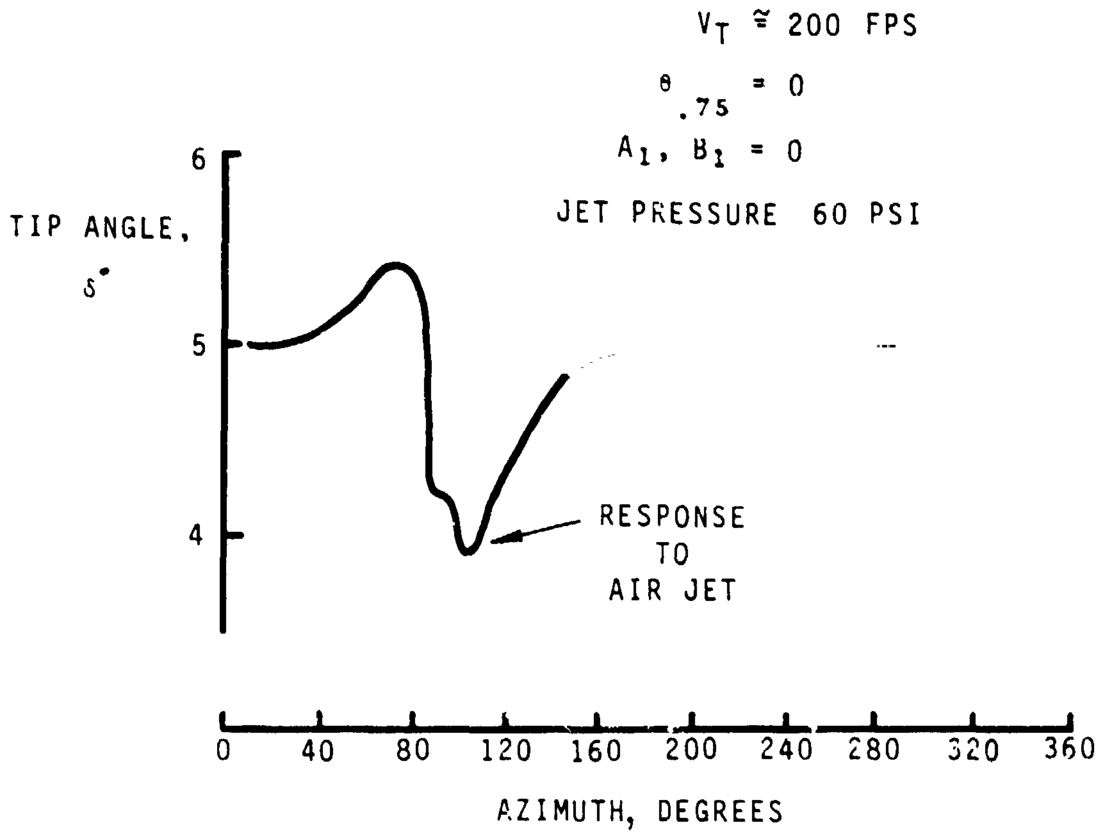

Figure 4.0a Response of Free-Tip to Air Jet in Hover

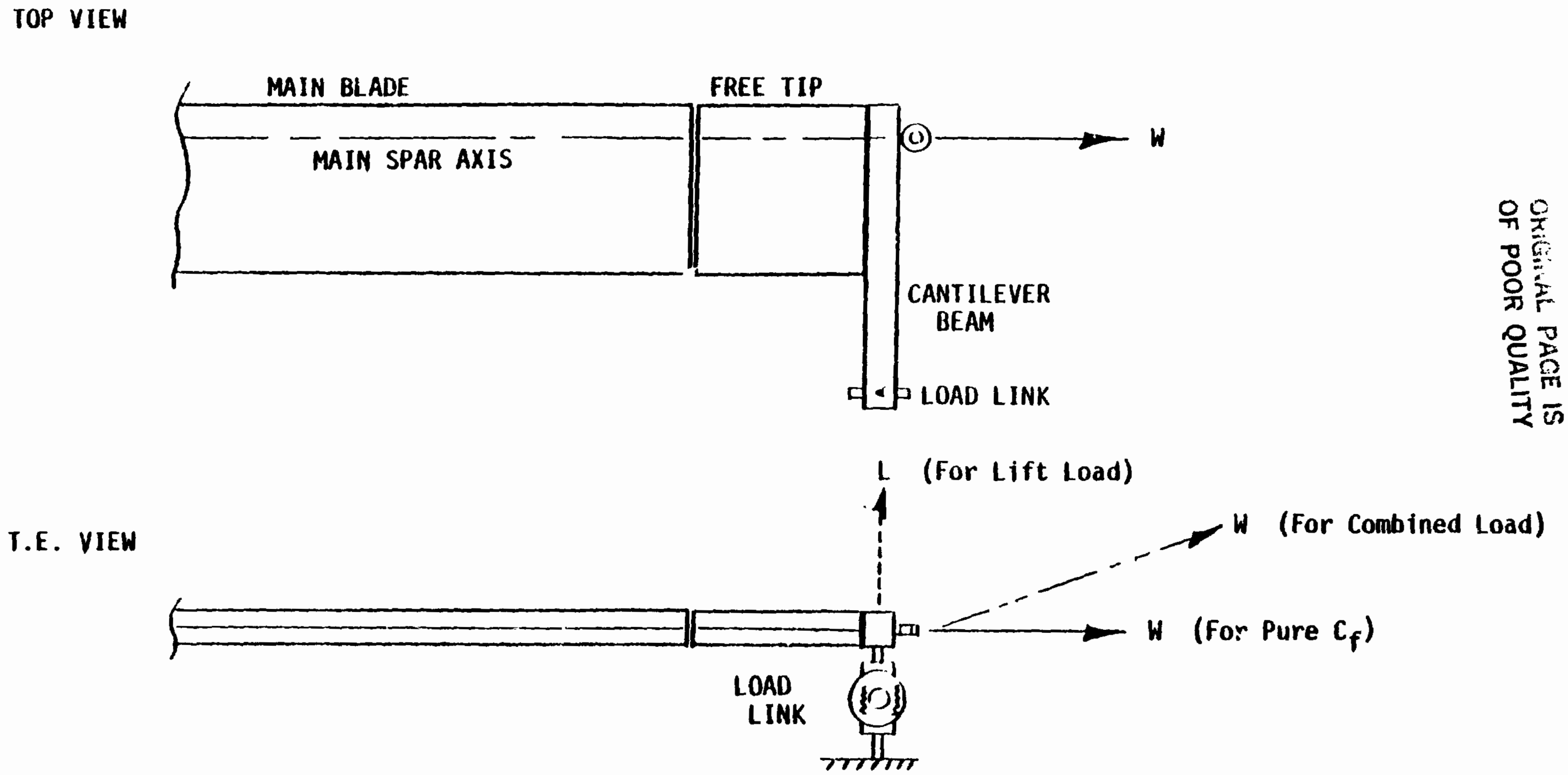

Figure 4.0b Test Arrangement for Friction Pull Test

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NUMBER
REV LTR

RUN NO.	CONFIGURATION	TYPE OF RUN	WT. TARE RUN	μ	q	RPM	$\theta^{\circ}_{.75}$	A_{1_c}	B_{1_c}	α°_s				DATE / TIME
2	K_1	WARM UP	2	0	0	796	0	0	0	▷1				4/20/81 1857
3	✓	HUB TARE	✓	.10	5.8	✓	12	1.5	5.1	✓				1901 1942
5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				1943 2013
6	✓	✓	✓	.20	23.1	✓	11.2	1.8	4.0	✓				2015 2107
7	✓	✓	✓	.25	35.9	✓	12.0	2.6	4.0	✓				2216 2233
8	✓	✓	✓	.30	51.	✓	13.5	3.0	5.0	✓				2235 2250
9	✓	✓	✓	.35	69.7	✓	14.5	3.5	6.2	✓				2252 2308
10	✓	✓ + CONTROL VAR.N	✓	✓	69.7	✓	▷2	▷3	▷4	✓				2310 2344
11	✓	HUB TARE	✓	.40	88.1	✓	16.6	3.8	8.0	✓				2346 0002
12	✓	✓	✓	.45		✓	18.8	3.5	6.7	✓				4/21/81 0003

2 K_1 = BASIC DRTS, NOSE FAIRING ON, GEAR BOX 16' DIA. ROTOR HUB, P.A AND P.L. UPPER STACK FAIRING FITTED.

$K_1 = H_1\ PA_1\ PL_1\ F_1\ F_2$ ▷1 $\alpha_s = -20°$ TO $\times 3°$'s.

WARM UP RUN ~ DATA EACH MIN AFTER ACHIEVING 796 RPM

3. DATA REDUCTION PROBLEM. DATA DOUBTFUL. REPEATED AS RUN 5 (4 ~ NG)

5. CYCLIC VALUES USED WERE S/PLATE VALUES

6 THIS RUN ON ~ VALUES OF CYCLIC ARE CORRECTED (CLASSICAL AXES) VALUES.

10 ▷4 : $B_{1_c} = 6.2 \pm 2$; ▷2 : $\theta_{.75} = 14.5 \pm 4$; ▷3 . $A_1 = 3.5 \pm 2$

CONTROL VARIATIONS @ α_s VALUES OF -11, -5, $+1$. ($\theta^{\circ}_{.75}$, THEN A°_1 THEN B°_1)

PREP.	KEF		REVISED	DATE	DRTS ~ CONSTANT LIFT TIP ~ HUB TARES	BVWT
CHK.						271
APPR						

FORM 46810 (3/70)

Figure 4.1 Test Run Log

RUN NO.	CONFIGURATION	TYPE OF RUN	WT. TARE RUN		μ'	RPM	$\theta^\circ_{.75}$	A_1°	B_1°	α_s°	C_T'/σ	$\bar{X}$	TIP ARRGT	DATE / TIME
13	$K_2 + VR16B001\text{-}1 + \overset{0}{B_3}\ \overset{90}{B_2}\ \overset{180}{B_1}\ \overset{270}{B_6} + W_2$	E_{TESC}	—		—	—	—	—	—	—	—	—	—	4/22/81
14	✓	—	—		—	—	—	—	—	—	—	—	—	
15	✓	SEE NOTE	2		0	796	0	0	0	0	—	—	FREE HIP WT.	0145
16	✓	WARM UP	✓		✓	✓	FOR C_T	0	0	0	.06	0	✓	0635 0705
18	✓	✓	18		✓	✓	✓	✓	✓	✓	✓	✓	✓	4/22 1802 1824
19	✓ [illegible]	C_T'/σ SWEEP	✓		✓	600	✓	✓	✓	✓	.07	✓	✓	1905 1925
20	✓ NO DATA	C_T'/σ SWEEP	✓		.20	796	✓	TRIM	TRIM	FOR $\bar{X}$	5	.05	✓	1927 1957
21	✓	FWD FLT.	✓		✓	✓	✓	✓	✓	8	✓	VAR	✓	2203 2312
22	✓	✓	✓	✓	.30	✓	✓	✓	✓	9	✓	✓	✓	2334
23	✓	✓	✓		.35	✓	✓	✓	✓	10	✓	✓	✓	4/23 0243 0357

13 ETESC

14 RUN ABORTED - COMPUTER PROBLEMS

15 TRACKING [illegible] BALANCE

16 WARM UP DEFINITION

17 ETESC ONLY.

18 WARM UP WITH DATA EVERY MINUTE. 1805 → 1822.

19 RUN @ C_T TO CHECK TRACK OF FREE TIP.

20 COMPUTER PROBLEM ~ RUN TERMINATED. ONLY DATA IS DUMMY CHECKOUT.

21 RUNNING C_T/σ SWEEPS AT VARIOUS α_s VALUES.

5: C_T'/σ = .04, .06, .08, .09 → MAX BY .01's

8: α_s = 0, -1°, -3°, -4° ; C_T'/σ TO .14

ADDED -2° (C_T'/σ .07 →).

AFTER RUN REPLACED WAX FILLER PLUG IN FREE TIP L.E.'S

22 9: α_s = -2, -5, -9, -12

α_s = +2, +4, +6, +7, +7.5 (AUTOROTATION)

10: α_s° = +5, -7, -9, -14, -2

PREP.			REVISED	DATE
CHK.				
APPR				

DRTS - CONSTANT LIFT TIP

FREE TIP

BVWT

271

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Figure 4.1 Test Run Log- Continued

THE **BOEING** COMPANY

NUMBER
REV LTR

RUN NO.	CONFIGURATION	TYPE OF RUN	WT. TARE RUN		μ'	RPM	$\theta_{.75}^{\circ}$	A_1°	B_1°	α_s'	C_T'/σ	$\bar{X}$	TIP ASSY.	DATE / TIME
24	$K_2+VR161B001\text{-}1+\overset{0}{B_3}\ \overset{90}{B_2}\ \overset{180}{B_1}\ \overset{270}{B_6}+W_2$ 1R	FF	18		.35	796	FOR C_T	FOR TRIM	FOR TRIM	▷11	.07	[illegible]	FREE [illegible]	4/23 0501
25	✓ ✓ ✓	✓	✓		▷12	✓	✓	✓	✓	-6	✓	✓	✓	0548
26	✓ ✓ ✓	✓	✓		.40	✓	✓	✓	✓	▷13	▷5	✓	✓	0617 0703
28	✓ NO DATA ✓ ✓	✓	✓		.30	✓	✓	✓	✓	▷9	✓	✓	FIXED SEALED	0630 [illegible]
29	✓ [illegible] ✓ ✓	✓	✓		.20	✓	✓	✓	✓	▷13	▷5	✓	FREE LIGHT	[illegible]
31	✓ [illegible] ✓ W_1	TBB	✓		0	✓	✓	✓	✓	-5	.07	✓	✓	
32	✓ ✓ ✓	FF	✓		.3	✓	✓	✓	✓	▷9	▷5	✓	✓	4/24 2239
33	✓ ✓ ✓	✓	✓		.35	✓	✓	✓	✓	✓	✓	✓	✓	4/25 0002 0029
34	✓ ✓ ✓	✓	✓		✓	✓	✓	✓	✓	▷10	▷5	✓	✓	4/27 0200
35	✓ FR ✓ ✓	✓	✓		✓	✓	✓	✓	✓	▷11	.07	.05	✓	0400

▷11 $\alpha_s = -6, -2, +4$ CONTROLS FIXED

▷12 $\mu = .3500, .3250, .3750, .3375, .3625$

▷13 $\alpha_s = -5, -7, -11$

26 ALSO AUTOROTATION @ $\alpha_s = +7°$, $C_T/\sigma = .07$

28 BLADE TIPS WITH LOCKOUT PINS IN. INITIALLY T.E WAS FURTHER RESTRAINED BY FIBERGLASS/EPOXY WRAP ROUND T.E AND GAP SEALED WITH WAX. THIS ALL DISAPPEARED ON CHECKOUT RUN. MOVEMENT IS NOW PREVENTED BY MYLAR TAPE WRAP RIGHT ROUND SECTION WITH ADDITIONAL STRIPS EACH SIDE OF GAP TO HOLD DOWN MAIN TAPE

29 RUN ABORTED - TIPS COMING FREE.

31 BALANCE O.K. CHECKOUT OF TV/STROBE SYSTEM FOR MEASURING α_T.

32 ADDED $\alpha_s = -7°$ AND AUTOROTATION @ $C_T/\sigma = .07$

33 $\alpha_s = -5°, -9°$ ONLY + TRIM PT @ $C_T/\sigma = .07$ $\bar{X} = .05$

Figure 4.1 Test Run Log- Continued

PREP.		REVISED	DATE	DRTS - CONSTANT LIFT TIP FREE & FIXED TIP	BVWT
CHK.					0271
APPR					

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RUN NO.	CONFIGURATION	TYPE OF RUN	WT. TARE RUN		μ'	RPM	$\theta^\circ_{.75}$	A_1°	B_1°	α_s°	C_T'/σ	$\bar{X}$	TIP ASSY	DATE / TIME
37	K_2 + VRK61B001-1 $B^{0\ 70\ 180\ 270}_{3\ 2\ 1\ 6}$ W_1	FF C_T SWEEP	18		.35	796	FOR C_T/σ	FOR TRIM FLAPPING		10	5	AS OBTAINED	FIXED LIGHT	4/27/81 2052 2215
38	✓ ✓ ✓ ✓	✓	✓		.30	✓	✓	✓	✓	9	✓	✓	✓	✓ 0200
39	✓ ✓ ✓ ✓	✓	✓		.40	✓	✓	✓	✓	FOR C_T/σ	16	✓	✓	0400
40	✓ ✓ ✓ ✓	FAN DIAG HOVER	✓		.40	SEE NOTE	✓	✓	✓	.02 $\bar{X}$	.07	.05	✓	0700
41	✓ ✓ NO DATA ✓ W_0	T, B	✓		0	796	0	✓	✓	0	—	—	FREE LOWER LIGHT	4/28/81
42	✓ ✓ NO DATA TAKEN	HOVER VIZ	✓		✓	✓	VAR	✓	✓	✓	VAR	—	✓	2123 2150
43	✓ ✓ ✓ ✓	HOVER	✓		✓	✓	VAR	✓	✓	✓	16	—	✓	2153 2214
44	✓ ✓ ✓ ✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	—	✓	2216 2232
45	✓ ✓ RPM SWEEP ✓	✓	✓		✓	17	FOR C_T/σ	✓	✓	✓	.07	—	✓	2234 2250
46	✓ ✓ ✓ ✓	F.F.	✓		.30	796	✓	✓	✓	18	5	—	✓	4/29/81 0012 0055

37 DID AUTOROTATION POINT @ C_T/σ = .07. LAST T.P.
POST RUN MODEL INSPECTION SHOWED LOCKOUT STRIP FAILURES ON S/N 1 AND 6.
THESE REPAIRED PRIOR TO RUN 38

AD RPM = 600(5.1) → 570

39 16

41 LOWER WEIGHT TIP

42 NO Δ WEIGHTS. 3/16" DIA TEETER WT. FROM MOVED TO 1/4" DIA LE HOLE

43 C_T/σ = 0 → MAX BY .01 MAX WAS .09 (POWER LIMIT)

44 REPEAT RUN 43 FOR DATA REPEATABILITY

16 C_T/σ = 0 → MAX BY .01

45 17 RPM = 400 → 850 X 50's

46 18 α_s = -2, -5, -9

PREP.			REVISED	DATE	DRTS - CONSTANT LIFT TIP FIXED TIP	BVWT
CHK.						0271
APPR						

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Figure 4.1 Test Run Log- Continued

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NUMBER
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RUN NO.	CONFIGURATION	TYPE OF RUN	WT. TARE RUN		μ'	RPM	$\theta^\circ_{.75}$	A_1°	B_1°	α_s°	C_T'/σ	$\bar{X}$	TIP ASSY	DATE / TIME
47	K_2 (VR 161 B001-1) B^{0}_{3}, $^{90}_{2}$, $^{180}_{1}$, $^{270}_{6}$ W_0	FF C_T SWP	18		.35	796	FOR C_T/σ	FOR FLAPPING	TRIM	18	5	–	FREE SWEPT	8/19/81 0100 0136
48	✓	✓	✓		.40	✓	✓	✓	✓	✓	✓	✓	✓	0218
49	✓ W_3	✓	✓		.30	✓	✓	✓	✓	✓	✓	✓	NO AFT FREE	0408
50	✓	✓	✓		.35	✓	✓	✓	✓	✓	✓	✓	✓	
51	✓	✓	✓		.40	✓	✓	✓	✓	✓	✓	✓	✓	0643

49 NO WEIGHTS IN TIP

16, 17, 18 } NOT USED

PREP.			REVISED	DATE
CHK.				
APPR				

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Figure 4.1 Test Run Log- Concluded

Flag Note Summary

1. α_s = -20^o to $+10^o$ by 3^o
2. θ_{75} = $14.5^o \pm 4^o$
3. A_1 = $3.5^o \pm 2^o$
4. B_{1C} = $6.2^o \pm 2^o$
5. C_T'/σ = .04, .06, .08, .09 → Max by .01's (Power Limit)
6. Not Used
7. Not Used
8. α_s^o = 0^o, -1^o, -3^o, -4^o
9. α_s^o = -12, -9, -5, -2, +2, +4, +6, +7, α_s for autorotation
10. α_s^o = -5, -7, -9, -12, -2
11. α_s^o = -6^o, ± 2, ± 4 about trim, controls fixed
12. μ' = .35, .325, .375, .3375, .3625
13. α_s = -5^o, -9^o, -11
14. Not Used
15. Not Used
16. C_T'/σ = 0 → Max by .01 (Power Limit)
17. RPM = 400 → 850 by 50
18. α_s = 2, -5, -9

Figure 4.2 Flag Note Summary

Component Descriptions

K_1 = Basic D.R.T.S. - Nose Fairing On
- 75:1 Gear Box
- Upper Stack Fairing

B_x = Blade Number X

W_o = Extra light weight

W_1 = Light weight tip

W_2 = Mid weight tip

W_3 = No weights in tip

Figure 4.3 Component Descriptions

5.0 TEST RESULTS AND ANALYSIS

The complete test data on the performance and vibratory loads of the free tip rotor are presented in detail in Appendix A. This section summarizes the main results of the test and presents a simple analysis which is used to explain some of the trends observed in the results.

5.1 Analysis

The analysis is based on the following simplifying assumptions:

1. Quasi-steady aerodynamics
2. Uniform downwash
3. Inelastic blade
4. Inviscid flow

With reference to Figure 5-1, let s be the chordwise coordinate, r the blade radial coordinate, t the local thickness, Ω the rotor rotational speed, β the flapping angle, and θ the pitch angle of the free tip at azimuth ψ. An element of mass located at r, s, t within the tip contributes to the pivot moment an amount

$$dM_{cf} = dm\,\Omega^2 r'(s-s_p)\left[\cos\varepsilon \sin\beta \cos\theta - \sin\theta \sin\varepsilon\right]$$

Since $r' \sin\varepsilon = (s-s_p)\cos\theta$
$r' \cos\varepsilon = r\cos\beta$

and $dm = \sigma\, dr\, ds\, dt$ (σ is blade mass density)

then the inertial moment about the pivot is

$$M_{cf} = \frac{1}{2}\Omega^2\left[\tilde{I} \sin 2\beta \cos\theta - I_p \sin 2\theta\right]$$

where I_p is the pitch inertia about the pivot
and $\tilde{I}$ is the product of inertia of the tip about the pivot line and the blade flapping axis.

The centrifugal force has a component in the direction of positive flapping,

$$Z_{cf} = -\frac{1}{2}\Omega^2 M_{FP} \sin 2\beta$$

where M_{FP} is the mass moment of the tip about the flapping pin.

In summary, the contributions from centrifugal force are a moment, M_{CF}, about the pivot and a force, Z_{CF}, normal to the blade acting through the pivot.

Referring to Figure 5-1, let Za be the aerodynamic force normal to the free tip, acting at the quarter chord, $M_{\frac{1}{4}}$ be the aerodynamic moment acting about the quarter chord line, M_F be the total moment exerted by the pivot on the tip, and R_{PIV} the force exerted by the pivot on the tip.

Resolving in the direction of positive flapping,

$$Z_a + Z_{cf} - R_{PIVOT} - W\cos\beta = \frac{W}{g}\left[R_G\ddot{\beta} + (S_P - S_G)\ddot{\theta}\right]$$

and taking moments about the tip center of mass,

$$Z_a(S_G - S_{\frac{1}{4}}) + (R_{PIVOT} - Z_{CF})(S_P - S_G) + M_{1/4} + M_F + M_{CF} = I_G\ddot{\theta}$$

Combining these eliminates the pivot reaction and yields

$$Z_a(S_P - S_{1/4}) - W(S_P - S_G)\cos\beta + M_{\frac{1}{4}} + M_F + M_{CF} = \frac{W}{g}(S_P - S_G)\left[R_G\ddot{\beta} + (S_P - S_G)\ddot{\theta}\right] + I_G\ddot{\theta}$$

For the c.g. lying on the pivot, $S_P = S_G$ and the pitch equation of motion reduces to

$$Z_a(S_P - S_{1/4}) + M_{\frac{1}{4}} + M_F + M_{CF} = I_G\ddot{\theta}$$

i.e., the tip motion is inertially uncoupled from the flapping motion of the blade.

Expressing the forces in terms of the blade motion

$$Z_a = \frac{1}{2}\rho V_T^2(x + \mu\sin\psi)^2 C_{L\alpha}\,\alpha\,S$$

$$M_{1/4} = \frac{1}{2}\rho V_T^2(x + \mu\sin\psi)^2 c S\left[\frac{\partial C_{M1/4}}{\partial C_L}C_L + C_{M_0}\right]$$

$$M_{CF} = -I_P\Omega^2\theta$$

where $C_{L\alpha}$ is the free tip lift-curve slope

C_{MO} is the quarter-chord pitching moment coefficient at zero lift

x is the mean radial distance of the free tip

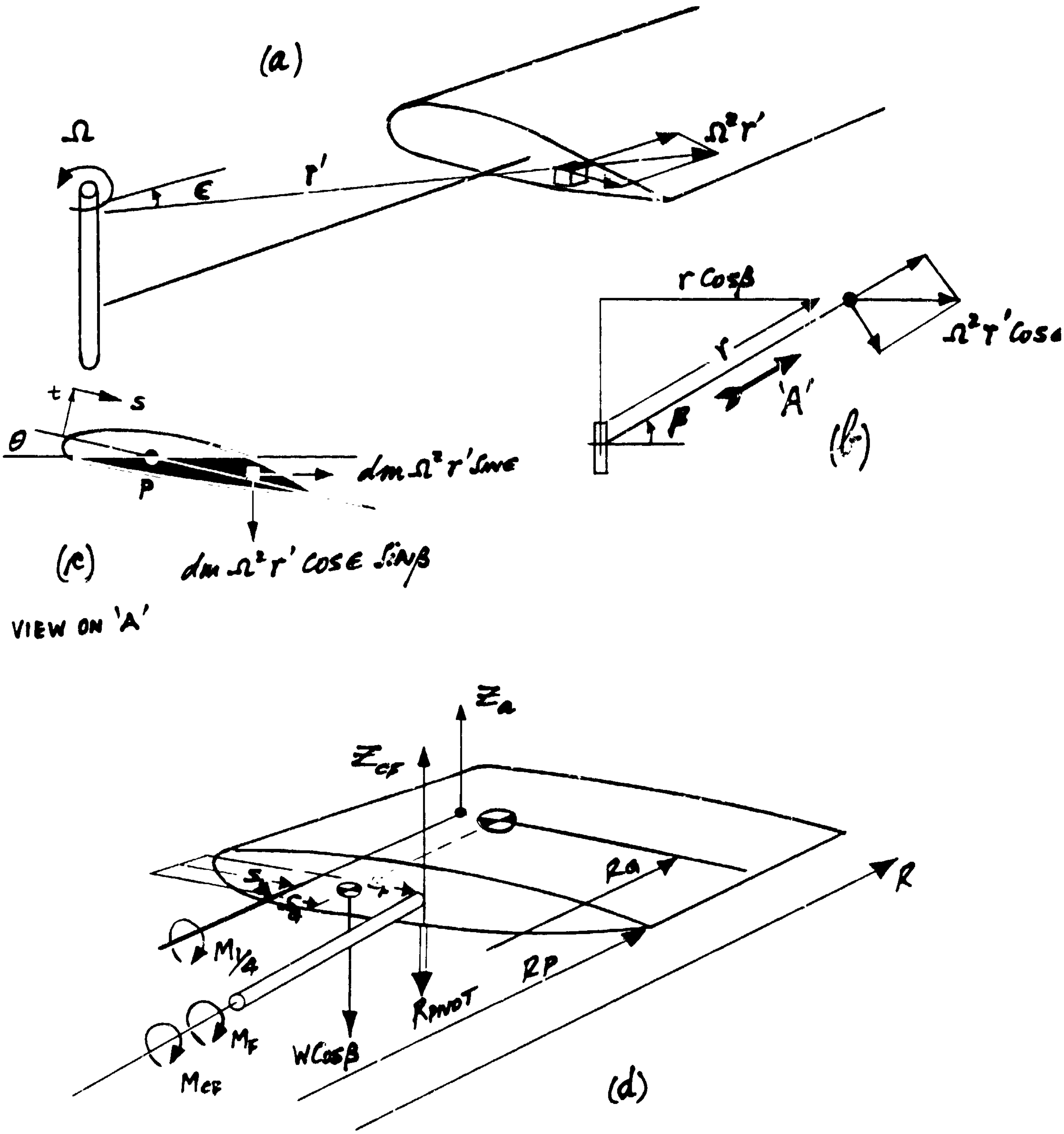

Figure 5.1 Notation

α is the tip angle of attack
and S is the tip reference area

Putting $\ell = s_p - c/4$, the pitch equation of motion becomes

$$\bar{\bar{\theta}} + \theta = \left[\frac{\frac{1}{2}\rho V_T^2 C_{L\alpha} S}{I_G \Omega^2}\left(\ell + c\frac{\partial C_{M1/4}}{\partial C_L}\right)\right]\alpha\,(x+\mu\sin\psi)^2$$
$$+ \frac{\frac{1}{2}\rho V_T^2 c S}{I_G \Omega^2} C_{M_0}\,(x+\mu\sin\psi)^2 + M_F/(I_G\Omega^2)$$

where $\bar{\bar{\theta}} = \partial^2\theta/\partial\psi^2$

Assuming a uniform downwash velocity v_i, the blade angle of attack is

$$\alpha = \theta - \frac{\bar{v}_i + x\bar{\beta} - \mu\sin\alpha_S}{x + \mu\sin\psi}$$

where $\bar{v}_i = v_i/V_T$ and $\bar{\beta} = d\beta/d\psi$

If the blade tip pitch motion is

$$\theta = \theta_0 - \sum_{N=1}^{\infty}\theta_{NS}\sin N\psi - \sum_{N=1}^{\infty}\theta_{NC}\cos N\psi$$

and if the first harmonic flapping motion is given by

$$\beta = a_0 - a_1\cos\psi - b_1\sin\psi$$

then by substitution in the equation of motion, and retaining only the first two harmonics of the pitching motion, the following set of equations is obtained for the blade pitch angle coefficients:

$$\left[a_{ij}\right]\begin{bmatrix}\theta_0\\ \theta_{1S}\\ \theta_{1C}\\ \theta_{2S}\\ \theta_{2C}\end{bmatrix} = \left[A_i\right]$$

Writing
$$P = \frac{1}{2}\rho \frac{V_T^2 C_{L\alpha} S}{I_G \Omega^2}\left[\ell + c\frac{\partial C_{H1/4}}{\partial C_L}\right]$$

$$Q = \frac{1}{2}\rho \frac{V_T^2 c S C_{H0}}{I_G \Omega^2}$$

$$S = M_F/(I_G \Omega^2)$$

$$\gamma = x^2 + \frac{1}{2}\mu^2$$

the coefficients a_{ij}, A_j are given in Figure 5-2.

In hover, $\mu = 0$ and $\gamma = x^2$, and the solution yields

$$\theta_{2s} = 0 = \theta_{2c}$$

$$\theta_{1s} = -a_1$$

$$\theta_{1c} = b_1$$

$$\text{and} \quad \theta_0 = \left[S + Qx^2 - Px k\sqrt{C_T}\right]/(1 - Px^2),$$

$$\text{since} \quad \bar{v}_i = k'\sqrt{\frac{C_T}{2(1-x_c^2)}} = k\sqrt{C_T}.$$

The interesting feature of this result is that in hover pitching motion of the free tip follows the flapping motion of the main blade and, further, if cyclic pitch is applied to the main blade, i.e.,

$$\theta_M = \theta_{.75} - A_{1c}\cos\psi - B_{1c}\sin\psi$$

$$= \theta_{.75} - b_{1c}\cos\psi + a_{1c}\sin\psi \quad (\text{in hover})$$

then the angle of the free tip relative to the main blade is

$$\delta = \theta_{TIP} - \theta_M$$

$$= \theta_0 - \theta_{.75} - \Delta\varepsilon$$

where $\Delta\varepsilon$ is the twist between the tip of the main blade and $x = .75$

$$\underbrace{\begin{bmatrix} 1-P\gamma & -P\mu x & 0 & 0 & -\frac{1}{4}P\mu^2 \\ 0 & P\gamma & 0 & 0 & -P\mu x \\ 0 & 0 & P\left[\gamma-\mu^2/4\right] & P\mu x & 0 \\ 0 & 0 & P\mu x & \left[3+P\gamma\right] & 0 \\ \frac{1}{2}P\mu^2 & P\mu x & 0 & 0 & 3+P\gamma \end{bmatrix}}_{a_{ij}} \begin{bmatrix} \theta_0 \\ \theta_{1s} \\ \theta_{1c} \\ \theta_{2s} \\ \theta_{2c} \end{bmatrix} = \underbrace{\begin{bmatrix} \delta + Qx + Px\mu\sin\alpha_s - \frac{P\mu x a_1}{2} - Px\bar{v}_i \\ 2\mu Qx + P\mu^2\sin\alpha_s - Px^2 a_1 - \frac{P\mu^2}{4} - P\mu\bar{v}_i \\ Px^2 b_1 \\ \frac{P\mu x b_1}{2} \\ \frac{P\mu x a_1}{2} - \frac{Q\mu^2}{2} \end{bmatrix}}_{A_i}$$

Figure 5.2 Coefficients a_{ij}, A_i

which is constant for a given thrust condition. Thus, the analysis shows that angle of the free tip with respect to the main blade will not change when cyclic pitch is applied in hover. This behavior was observed during the hover testing.

The nose-up moment exerted by the pivot on the free tip is proportional to the centrifugal force acting on the tip and can be shown to be given by (see Figure 5.3)

$$M_F = \frac{W\Omega^2 R_X}{3}\left(\frac{d_1^3 - d_0^3}{d_1^2 - d_0^2}\right)\left[\frac{\operatorname{Tan}\alpha - \bar{\mu}\,\operatorname{SIGN}(\dot{\delta})}{1 + \bar{\mu}\,\operatorname{Tan}\alpha\,\operatorname{SIGN}(\dot{\delta})}\right]$$

where d_1, d_0 are the outer and inner diameters of the helical contact surface between the follower pin and the guide,

α is the helical screw angle,

$\bar{\mu}$ is the coefficient of friction between pin and guide,

and $\dot{\delta}$ is the pitch rate of the free tip.

5.2 Test Results

As stated earlier, the complete test data is presented in Appendix A. Only the main points are discussed here.

5.2.1 Hover Performance

Hover performance was measured with the tip free at the light weight condition. No data was taken with the tip fixed, so a direct assessment of the effect of the free tip on hover performance cannot be made. An indirect assessment was obtained, however, using theory. Figure 5.4 shows the measured variation of power with thrust, Figure 5.5 shows the corresponding figure of merit and Figure 5.6 shows the angle of the free tip relative to the main blade. Theoretical calculations of hover performance were made using Boeing computer program B92 by treating the free tip angle as a step change in blade twist. The predictions of rotor power coefficient corresponding to the measured tip angles and thrust coefficients are shown on Figure 5.4 and the figure of merit on Figure 5.5.

Agreement between measured and predicted performance is good and shows that the tip angle was measured correctly. Also shown on these figures is the predicted performance for the tip fixed ($\delta = 0$). A general reduction in hover performance is predicted

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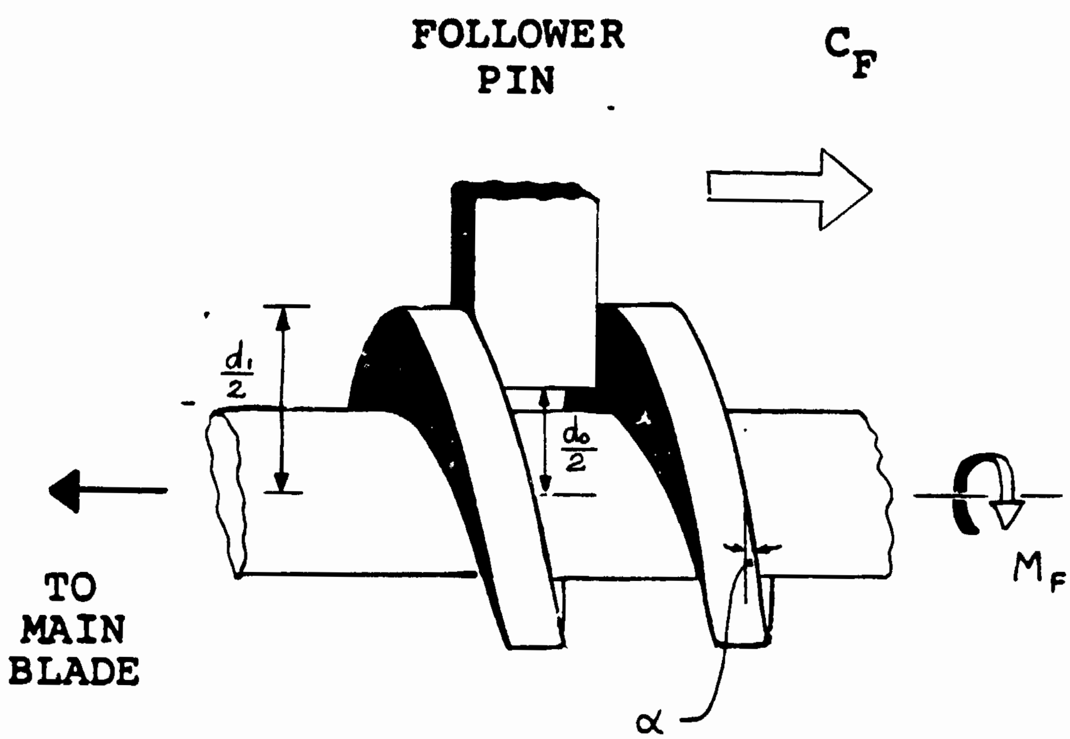

Figure 5.3 Pivot Screw Geometry

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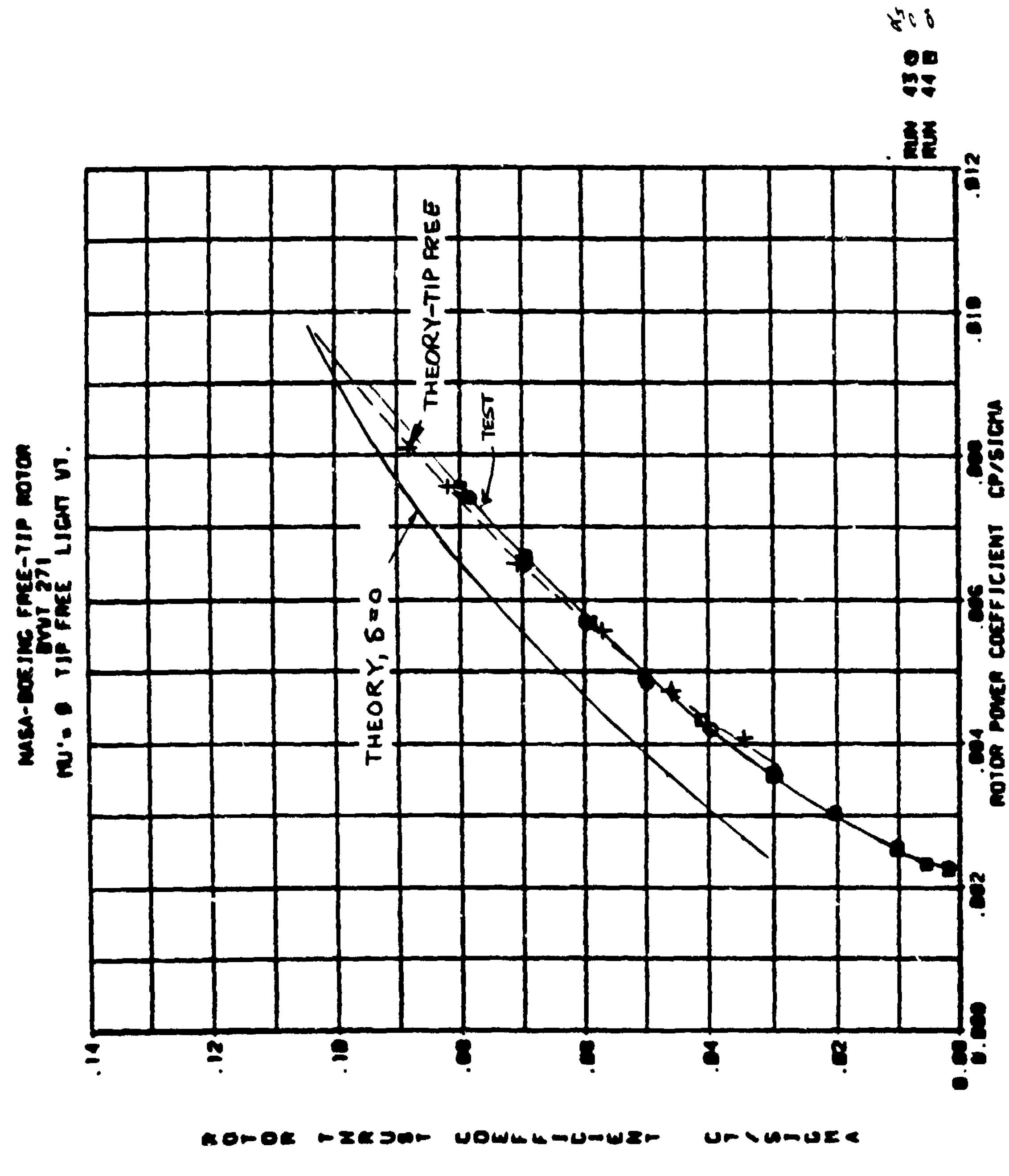

Figure 5.4 Measured Rotor Power Required with Tip Free and Comparison with Theory

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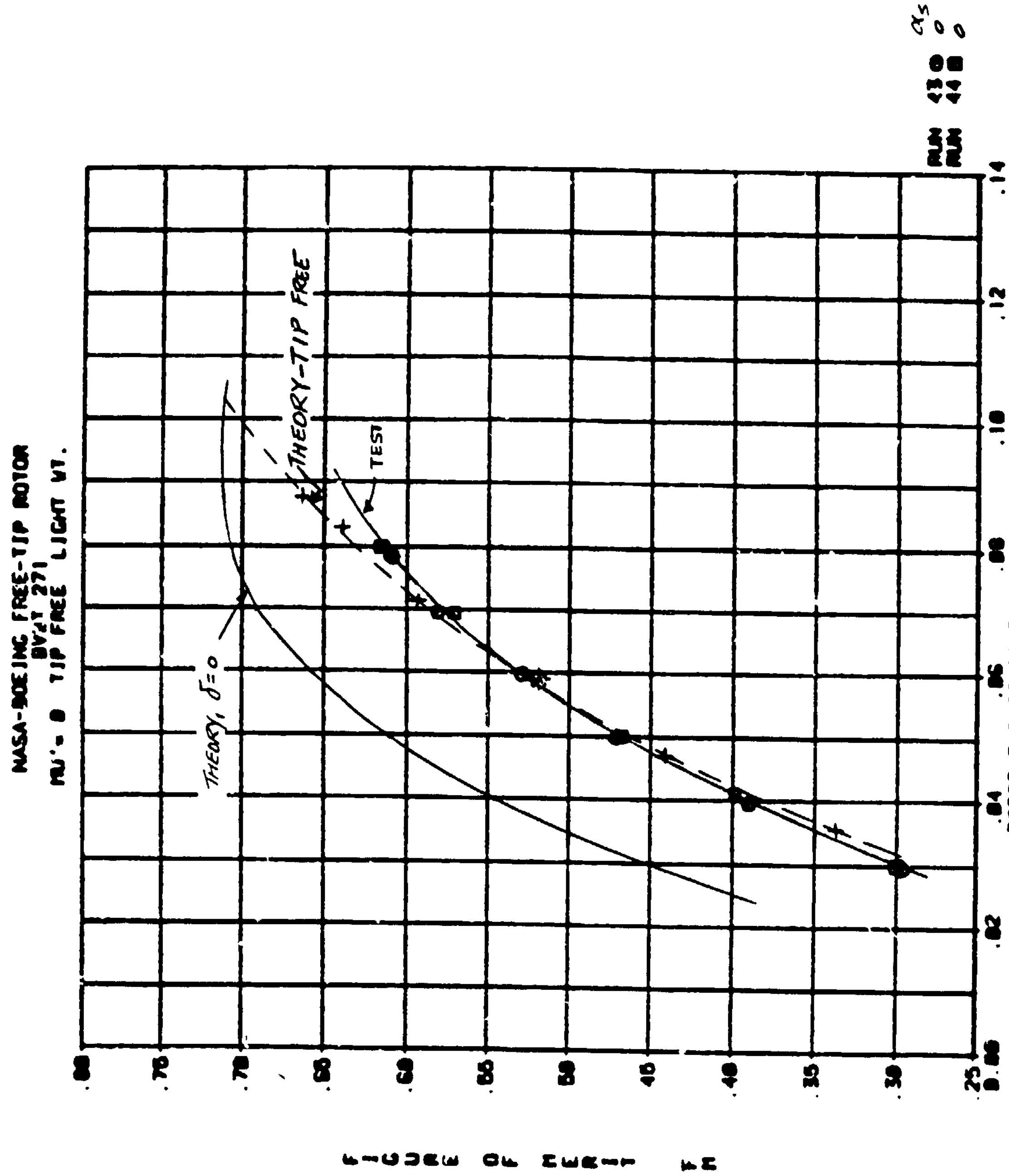

Figure 5.5 Variation of Figure of Merit with Thrust Coefficient with Tip Free and Comparison with Theory

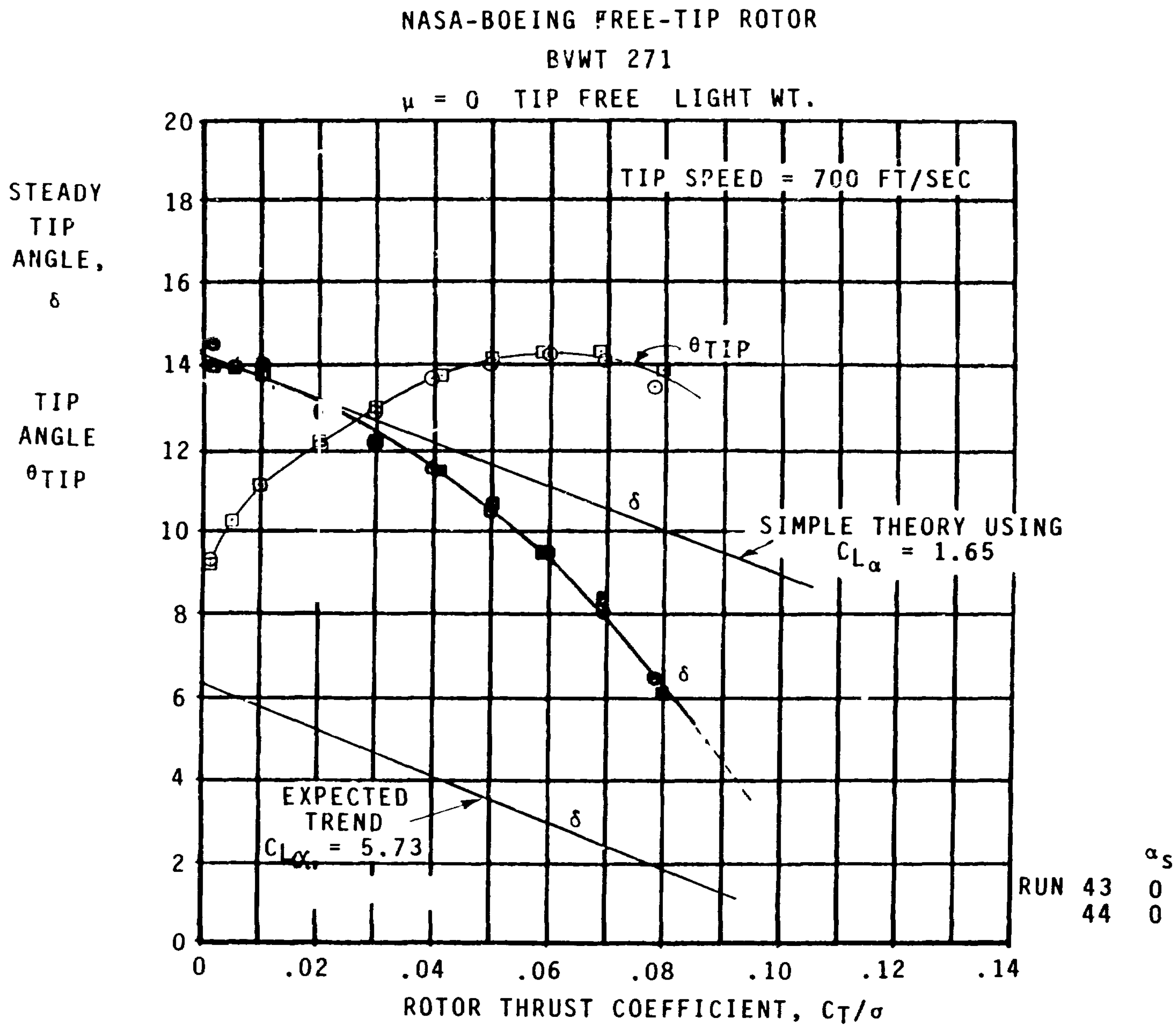

Figure 5.6 Variation of the Tip Angle, δ, and Comparison with Analysis

for the rotor with the tip free. At C_T/σ = .088, the reduction in figure of merit is estimated to be 7%.

Figure 5.6 shows the variation of the steady tip angle with rotor thrust coefficient. Also shown is the prediction of the simple analysis described above. In making the calculations, the variation of the tip lift-curve slope and aerodynamic center position with aspect ratio given in Figures 5.7 and 5.8 was used.

5.2.2 Forward Flight Performance

5.2.2.1 Effect of Free Tip on Power Required

Results from the forward flight testing show that, for the same propulsive force and lift, the rotor requires more power with the tip free than with it locked. The data of Figure 5.9 is typical. The plot shows the variation of power with advance ratio at C_T'/σ = .06 and $\bar{x}$ = .05 with the tip free at mid weight and with the tip fixed. At μ = 0.4, the increase in power required is 23% and at μ = 0.3 it is 27%. The corresponding lift-to-effective drag ratios are shown in Figure 5.10. The collective pitch settings are plotted in Figure 5.11, which shows that approximately 0.5° less collective is required with the tip free.

5.2.2.2 Effect of Thrust Level on Tip Response

The azimuthal variation of the free tip angle with changes in rotor lift is presented in Figures 5.12 through 5.16. The data was obtained at μ = 0.3 for the mid weight tip. The fact that propulsive force varies from case to case does not substantially change the general trends observed. The free tip angle, δ, is the angle of the tip measured relative to the inboard main blade. The angle of the tip relative to the disc plane (i.e., the local blade angle, θ_{TIP}) was calculated knowing δ and the collective and cyclic inputs. Both δ and θ_{TIP} are presented in the figures.

From the plots, it can be seen that the maximum variation of the relative tip angle δ over the azimuth is about 0.3 degrees for C_T/σ = .0409. As the thrust is increased, the average value of δ falls and more variation occurs around the azimuth until at C_T'/σ_T =.12144 fluctuations of 0.8 degrees occurs in the fourth quadrant of the disc. In terms of the tip blade angle, θ_{TIP}, at low C_T/σ the minimum value is approximately 10 degrees and occurs at $\psi = 150^{\circ}$. The maximum value is 14.5° occurring at 330° azimuth. As thrust is increased, the minimum value of θ_{TIP} increases slightly to 11 degrees at C_T/σ_T = 0.12144 but th maximum value rises to 25 degrees at 310° azimuth. The large blade tip angles encountered on the first and fourth quadrants suggest that the tip is in a stalled condition which would be consistent with the increased power observed.

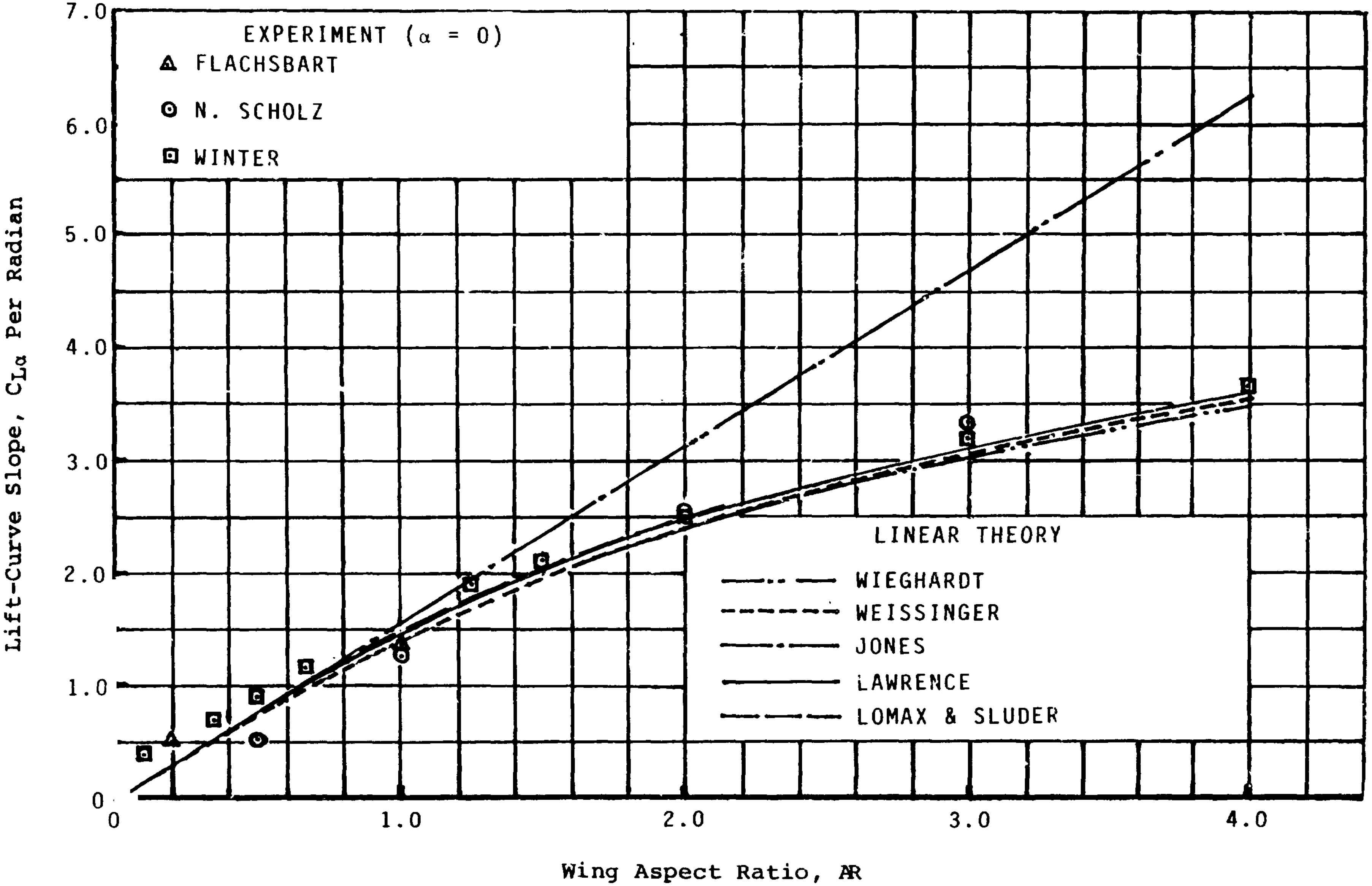

Figure 5.7 Variation of Lift-Curve Slope with Aspect Ratio
(From Reference 3)

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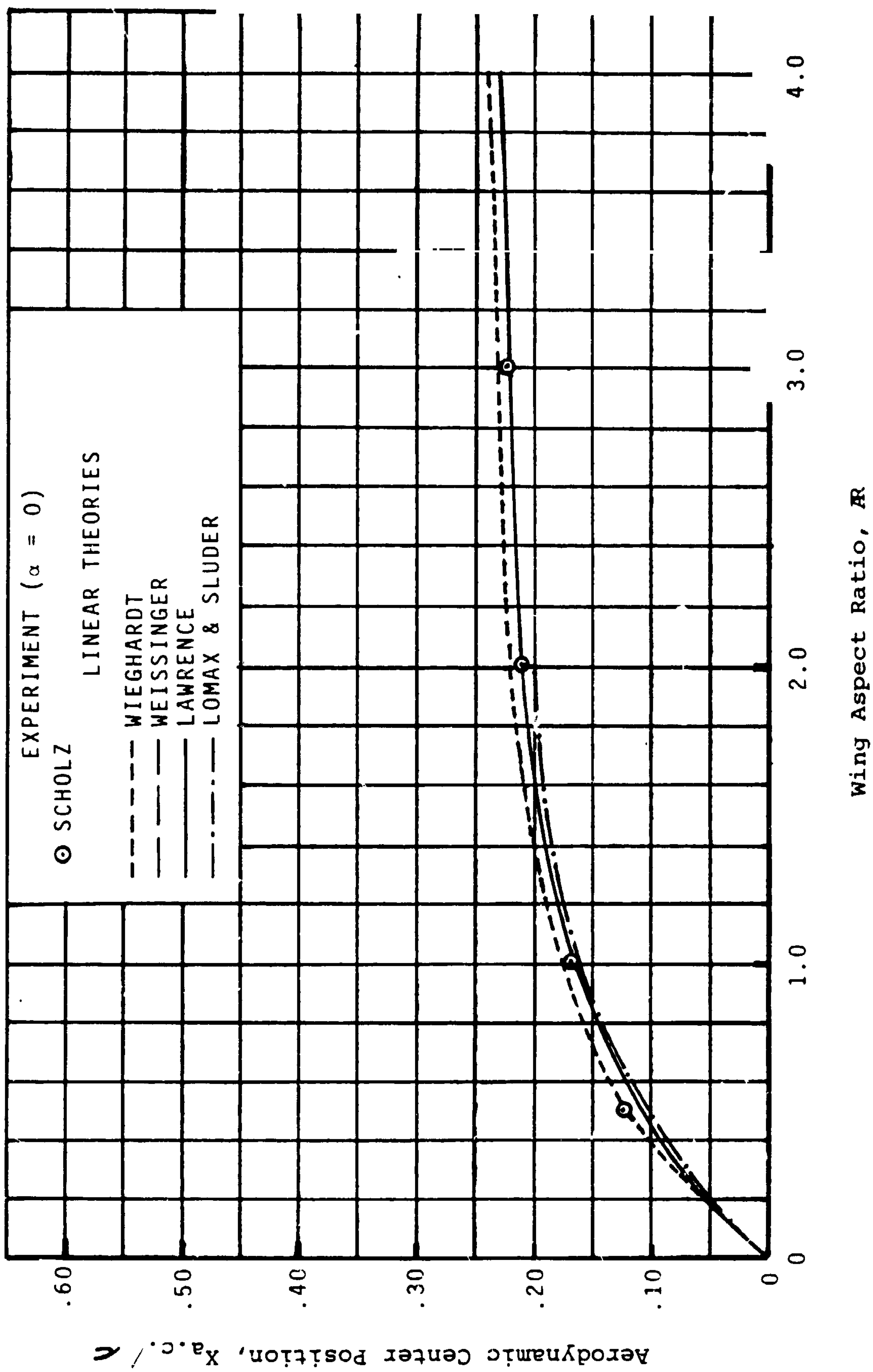


Figure 5.8 Variation of Aerodynamic Center with Aspect Ratio
(From Reference 3)

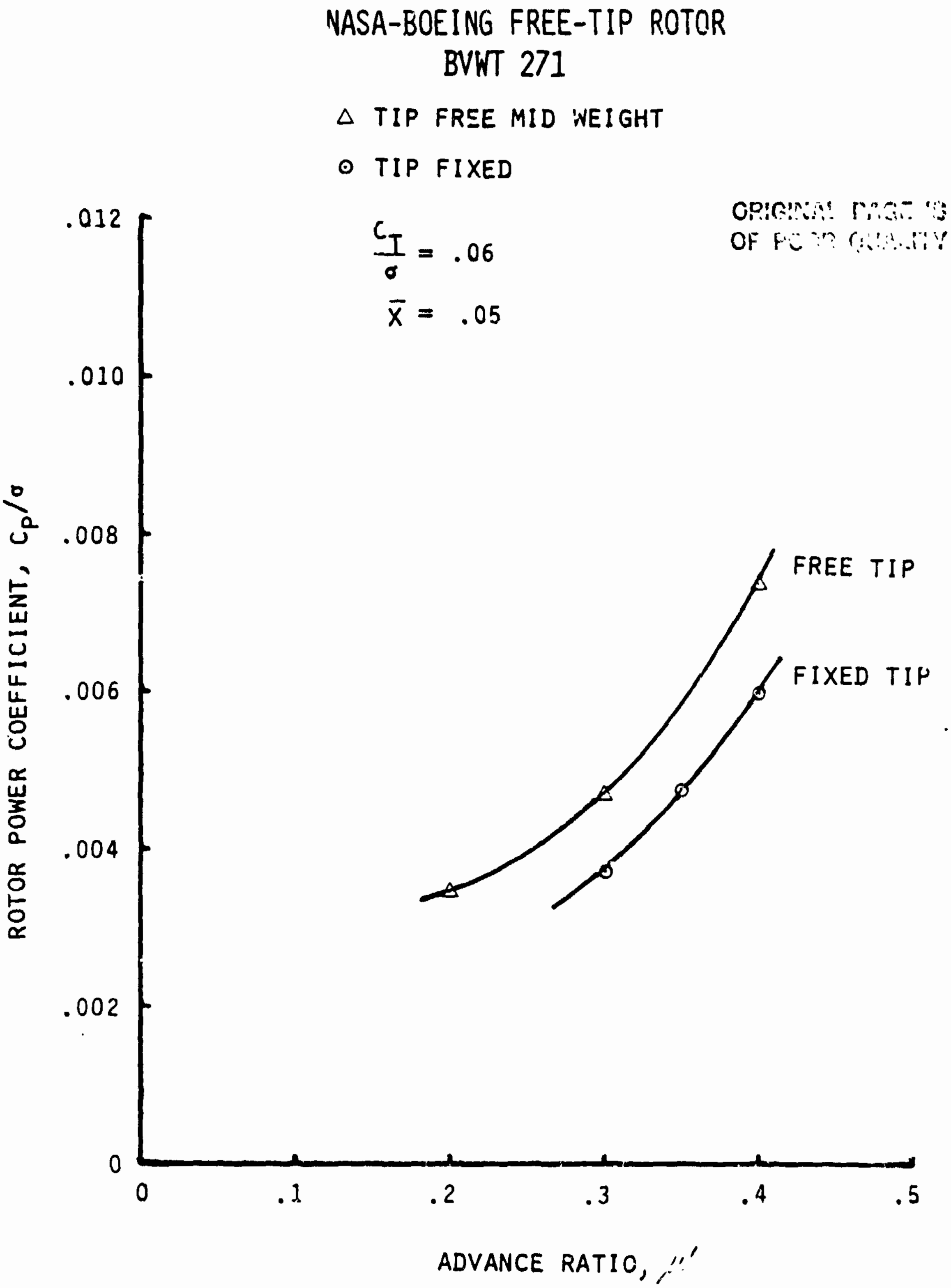


Figure 5.9 Comparison of Power Required, Tip Fixed and Free

NASA-BOEING FREE-TIP ROTOR
BVWT 2/1

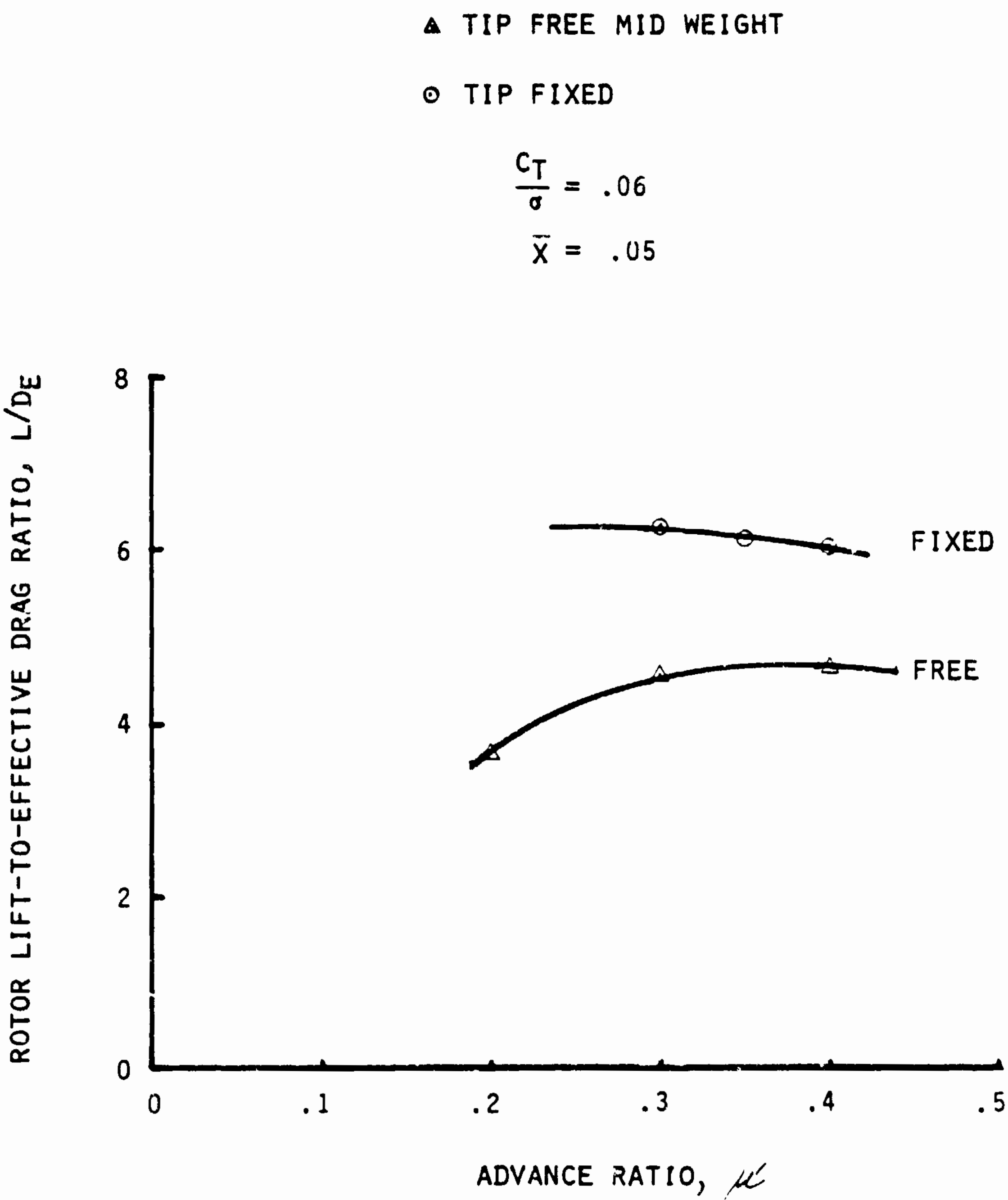


Figure 5.10 Comparison of Rotor Lift-to-Effective Drag Ratio, Tip Fixed and Free

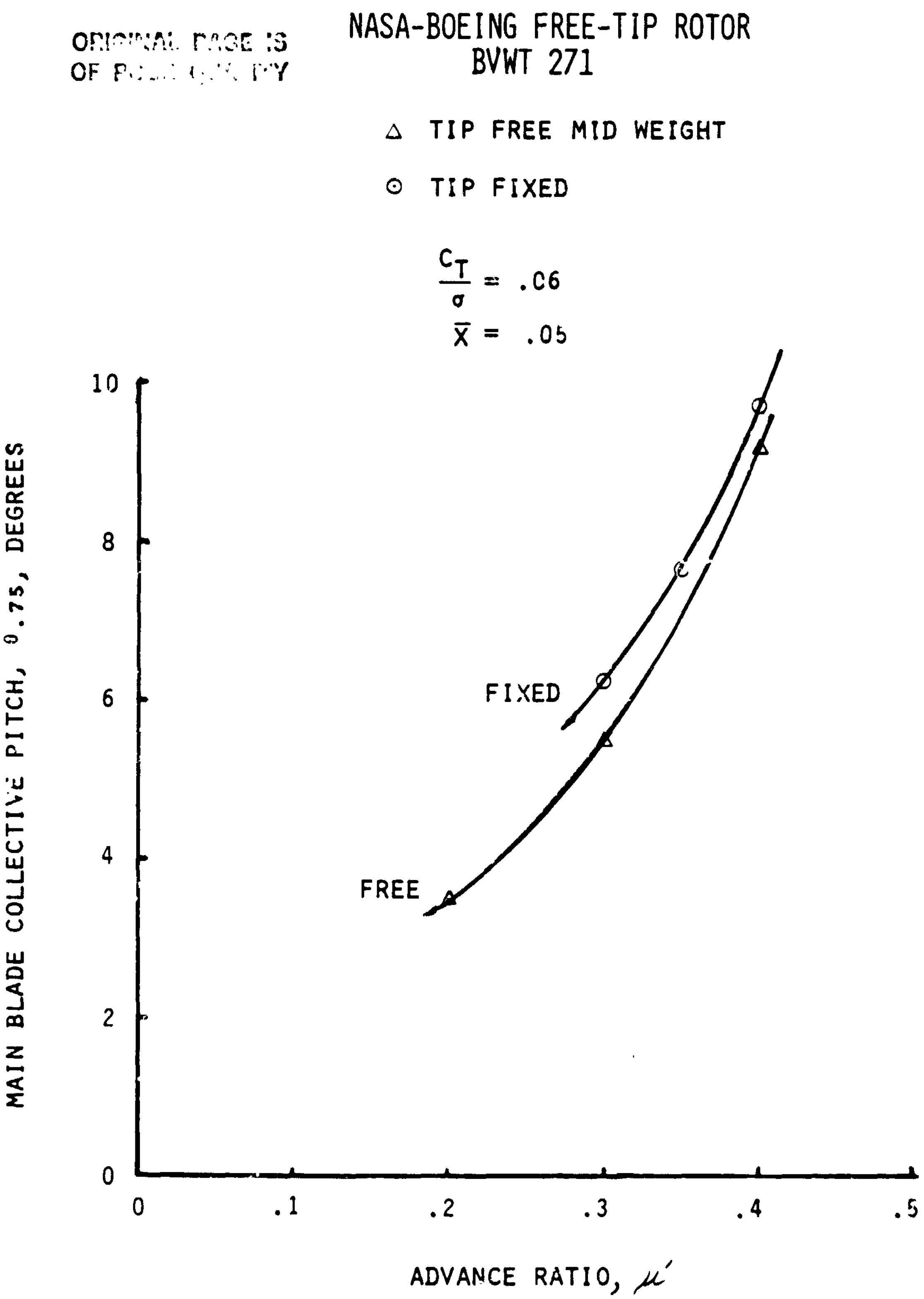
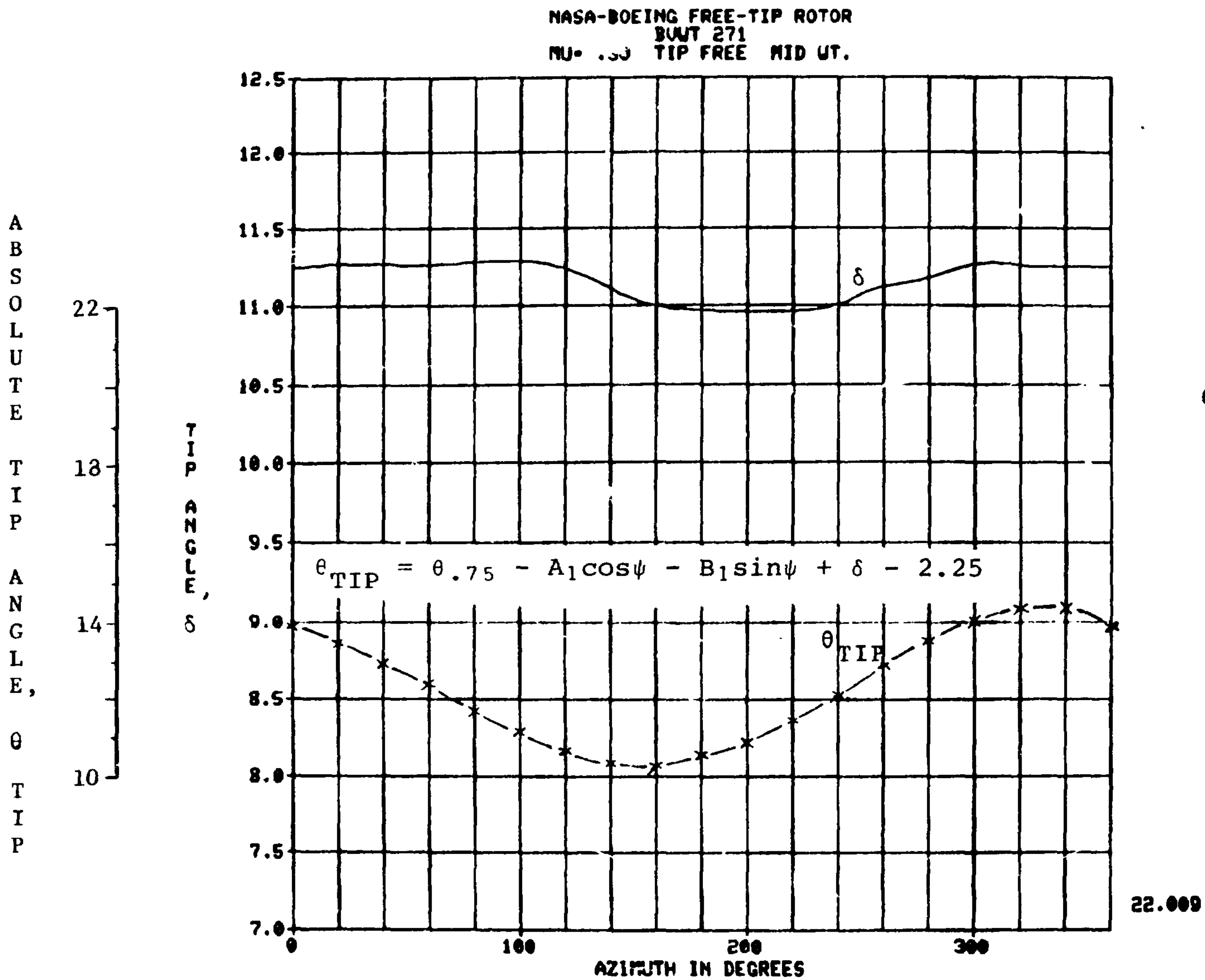


Figure 5.11 Comparison of Main Blade Collective Pitch, Tip Fixed and Free



$C_T'/\sigma = .0409$

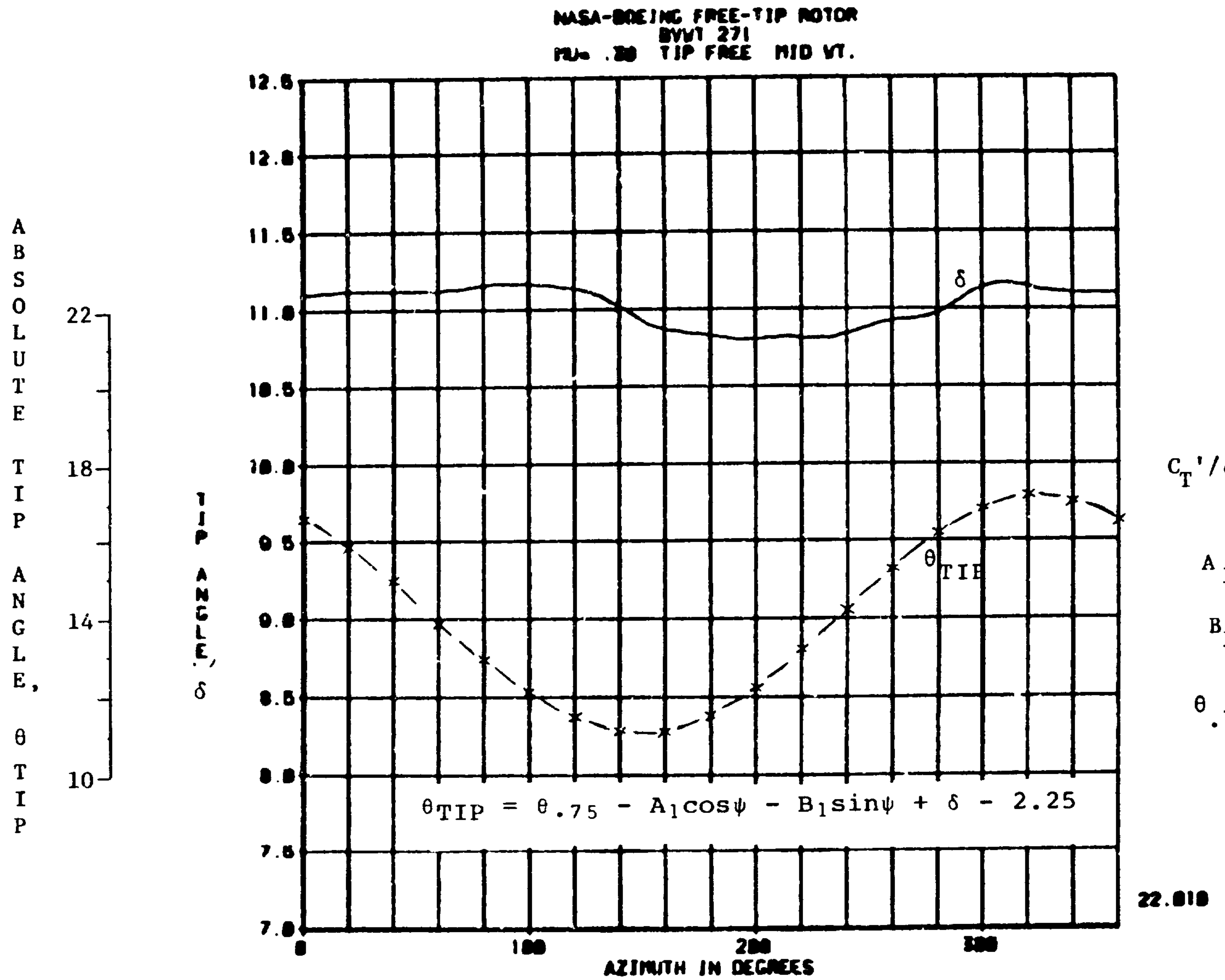
$\bar{X} = .01634$

$A_{1_c} = -1.592$

$B_{1_c} = .95388$

$\theta_{.75} = 3.3731$

Figure 5.12 Tip Response at $\mu = .30$, $C_T'/\sigma = .0409$



$C_T'/\sigma = .0612$

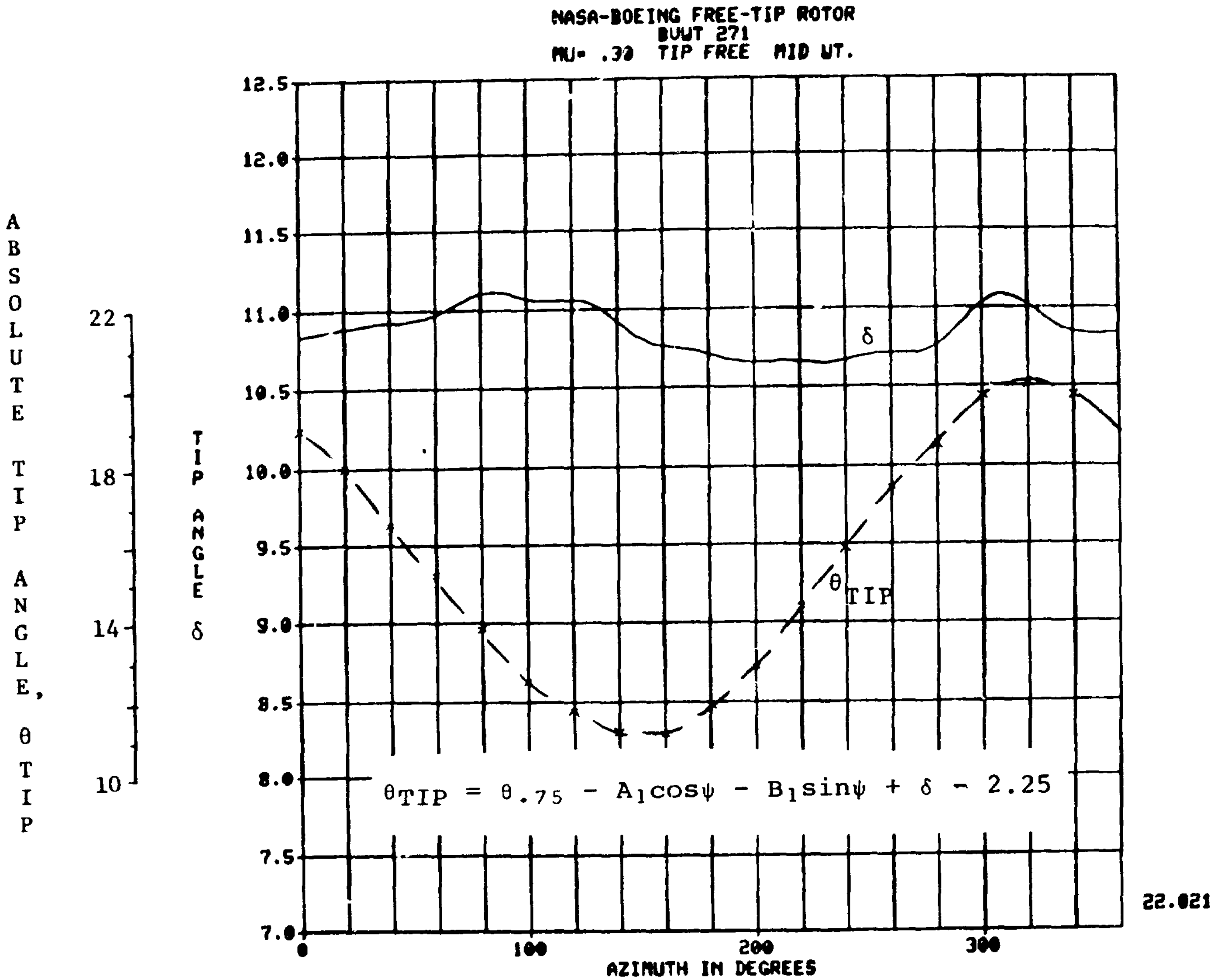
$\bar{X} = .04005$

$A_{1_c} = -2.375$

$B_{1_c} = 1.7728$

$\theta_{.75} = 5.304$

Figure 5.13 Tip Response at $\mu = .30$, $C_T'/\sigma = .0612$



C_T'/σ = .0843

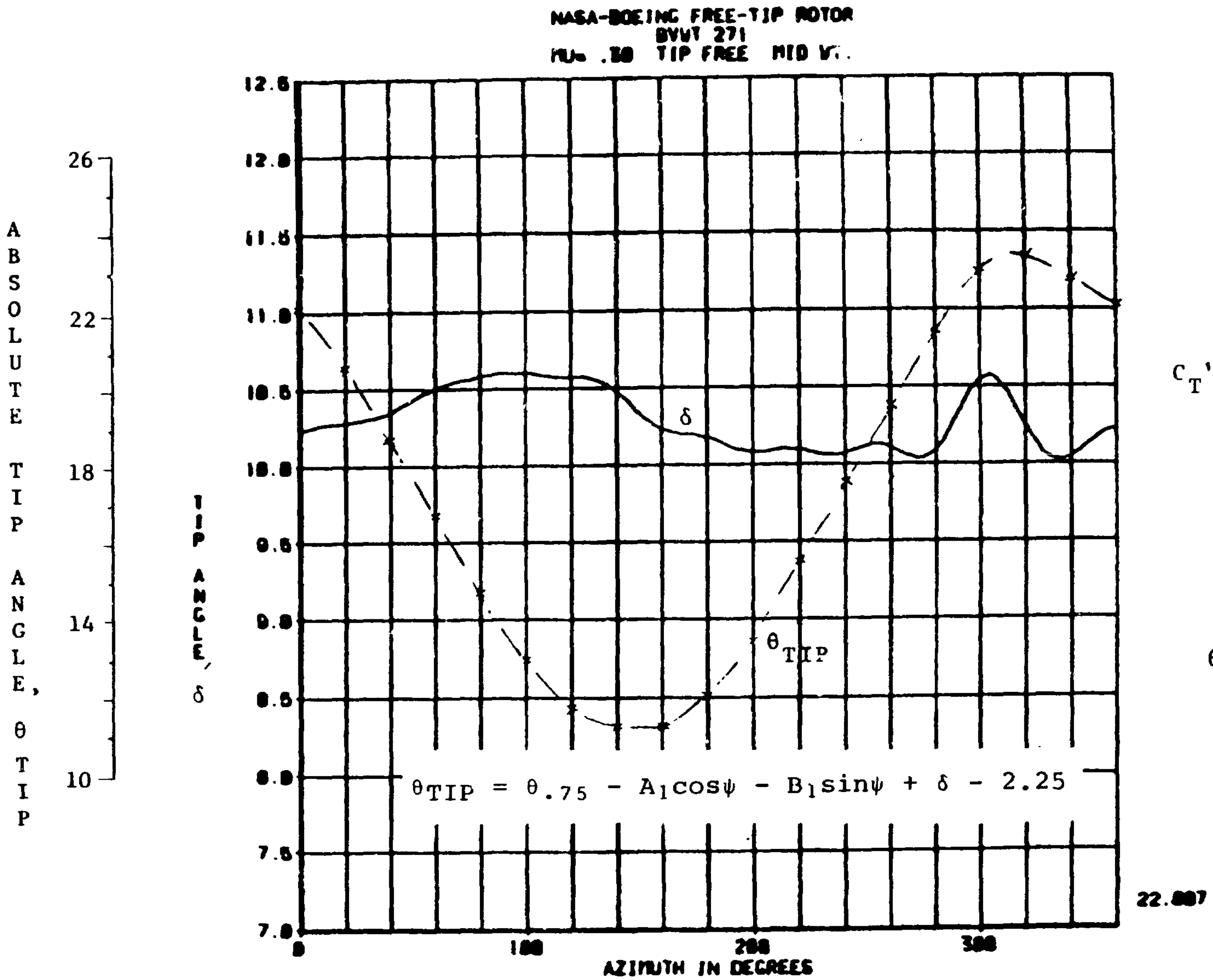
$\bar{X}$ = .03199

A_{1_c} = -3.4889

B_{1_c} = 2.6065

$\theta_{.75}$ = 6.9747

Figure 5.14 Tip Response at μ = .30, C_T'/σ = .0843



$C_T'/\sigma = .1113$

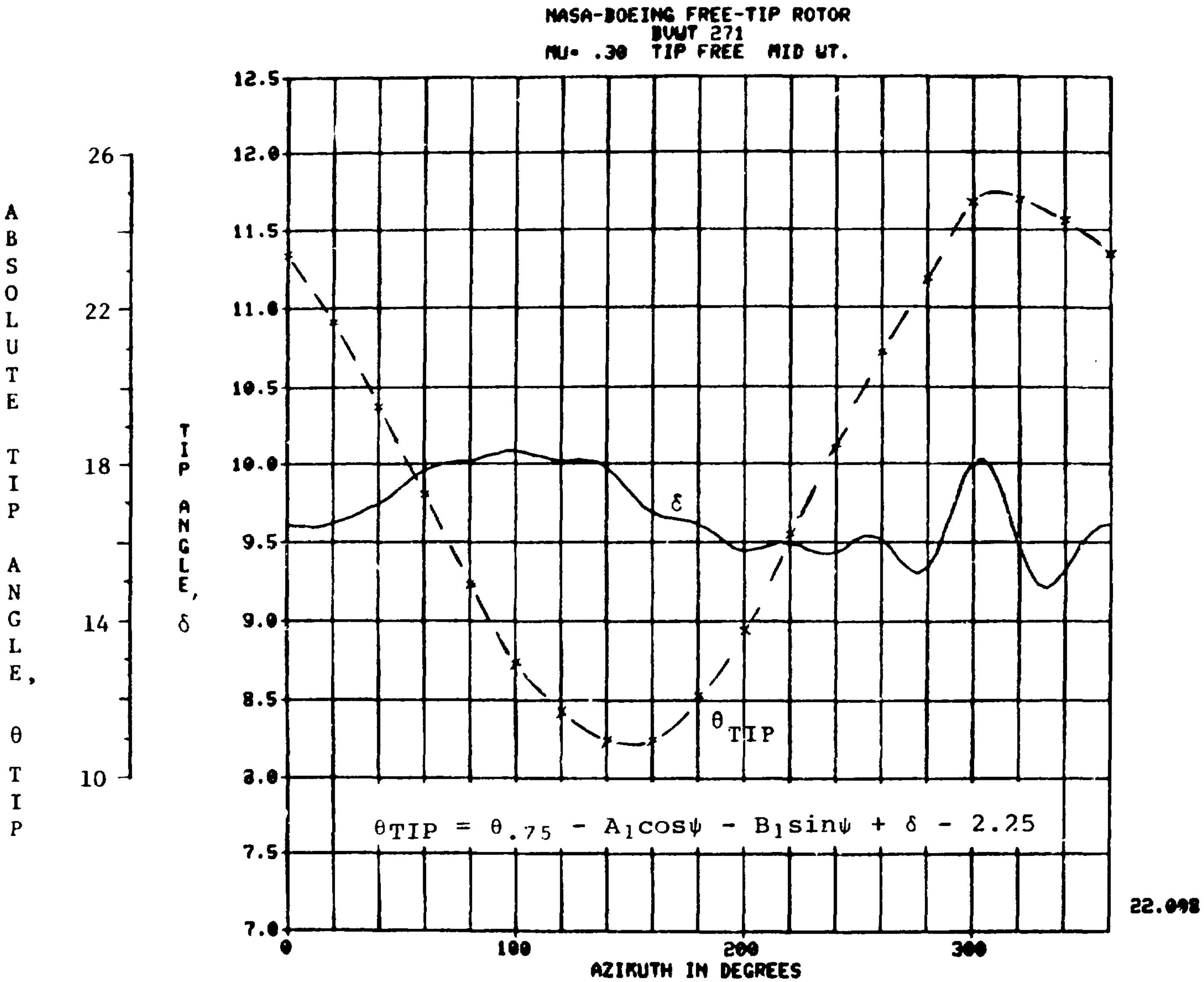
$\bar{X} = .007689$

$A_{1_c} = -4.9796$

$B_{1_c} = 3.6512$

$\theta_{.75} = 9.1444$

Figure 5.15 Tip Response a $\mu = .30$, $C_T'/\sigma = .1113$



$C_T'/\sigma =$ 12144

$\bar{X} = .02147$

$A_{1_c} = -5.6471$

$B_{1_c} = 4.3129$

$\theta_{.75} = 10.449$

Figure 5.16 Tip Response at $\mu = .30$, $C_T'/\sigma = .12144$

5.2.2.3 Effect of Tip Weight on Tip Response

The effect of tip weight and inertia on tip response is summarized in Figure 5.17, which shows the azimuthal variation of relative tip angle δ for the tip with mid weight, light weight, extra light weight and no tip weights added. For all cases the rotor lift is the same and approximately the same propulsive force is being produced. As the tip becomes lighter, the nose-up moment produced by the screw controller decreases and hence it would be expected that tip equilibrium would be reached at progressively lower tip angles. This is, in fact, what is observed and tends to confirm that the tip was operating freely.

Another expectation is that tip response would be increased at reduced tip inertia and weight. Again this is in accord with the measured tip behavior, as can be seen from Figure 5.17.

5.2.3 Vibratory Hub Loads

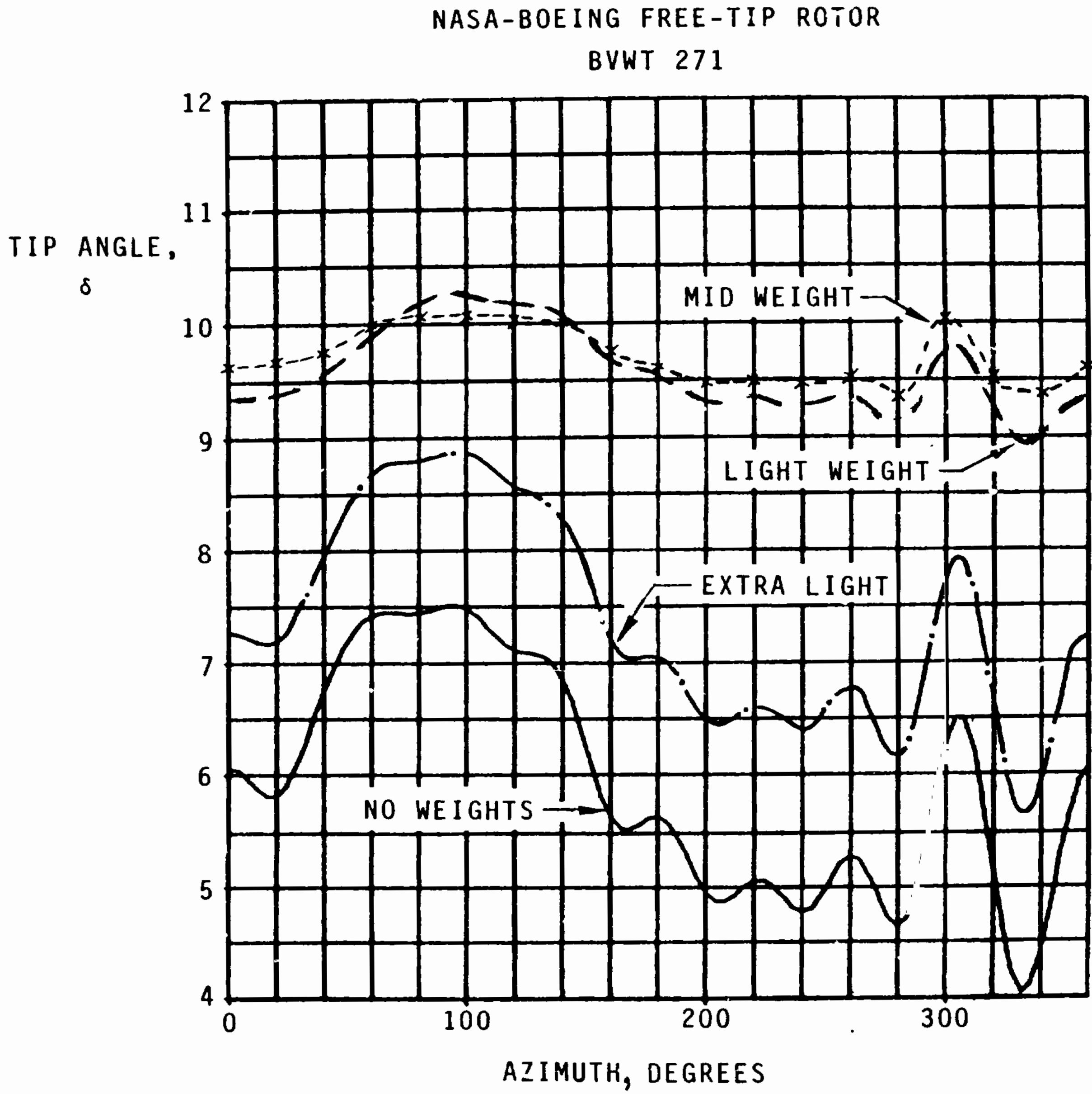
Throughout the test, hub vibratory forces and moments were measured. The 4/rev resultant in-plane and out-of-plane vibratory hub loads are plotted in Appendix A. It should be noted that these vibratory loads are uncorrected for any dynamic amplification that may have been present in the rotor test stand and hub. The data should not, therefore, be used as absolute quantities, though they may be used to make comparisons between tip configurations.

A typical finding of the test concerning vibratory hub loads is shown in Figures 5.18 and 5.19. Figure 5.18 compares the 4/rev vertical hub force with the tip fixed and free. With the tip free, the hub loads are about double those measured with the tip fixed. Figure 5.19 presents the corresponding resultant 4/rev in-plane force. In this instance, the free tip reduces the in-plane loads by 45% at $\mu = .3$ and by 16% at $\mu = .4$.

5.3 Discussion

The test results show that with the tip free, rotor performance was reduced in both hover and forward flight. The measured tip angle in hover (Figure 5.6) revealed that the tip was deflected nose-up by as much as 14° relative to the main blade. This introduces an effective positive tip twist to the rotor which is in the opposite direction to that needed to improve hover performance. As shown by the comparison with theory (Figures 5.4 and 5.5), the reduced hover performance is caused by the unfavorable twist.

The free tip was designed, and the pivot location selected at 13% chord so that the tip would operate at a $C_L = 1.15$ on the retreating side of the rotor disc at $\mu = .35$. A value for the tip lift-curve slope of 5.73 per radian was used and the aerodynamic



$\mu = .30$
TIP FREE

WEIGHT COND.	RUN	TP	C_T'/σ	$\bar{X}$	SYMBOL
LIGHT	32	8	.1203	.03315	— —
EXTRA LIGHT	46	9	.1199	.0343	—·—
NO WEIGHTS	49	8	.1203	.0356	——
MID	22	8	.12144	.02147	x--x--x

Figure 5.17 Effect of Tip Weights on Tip Response

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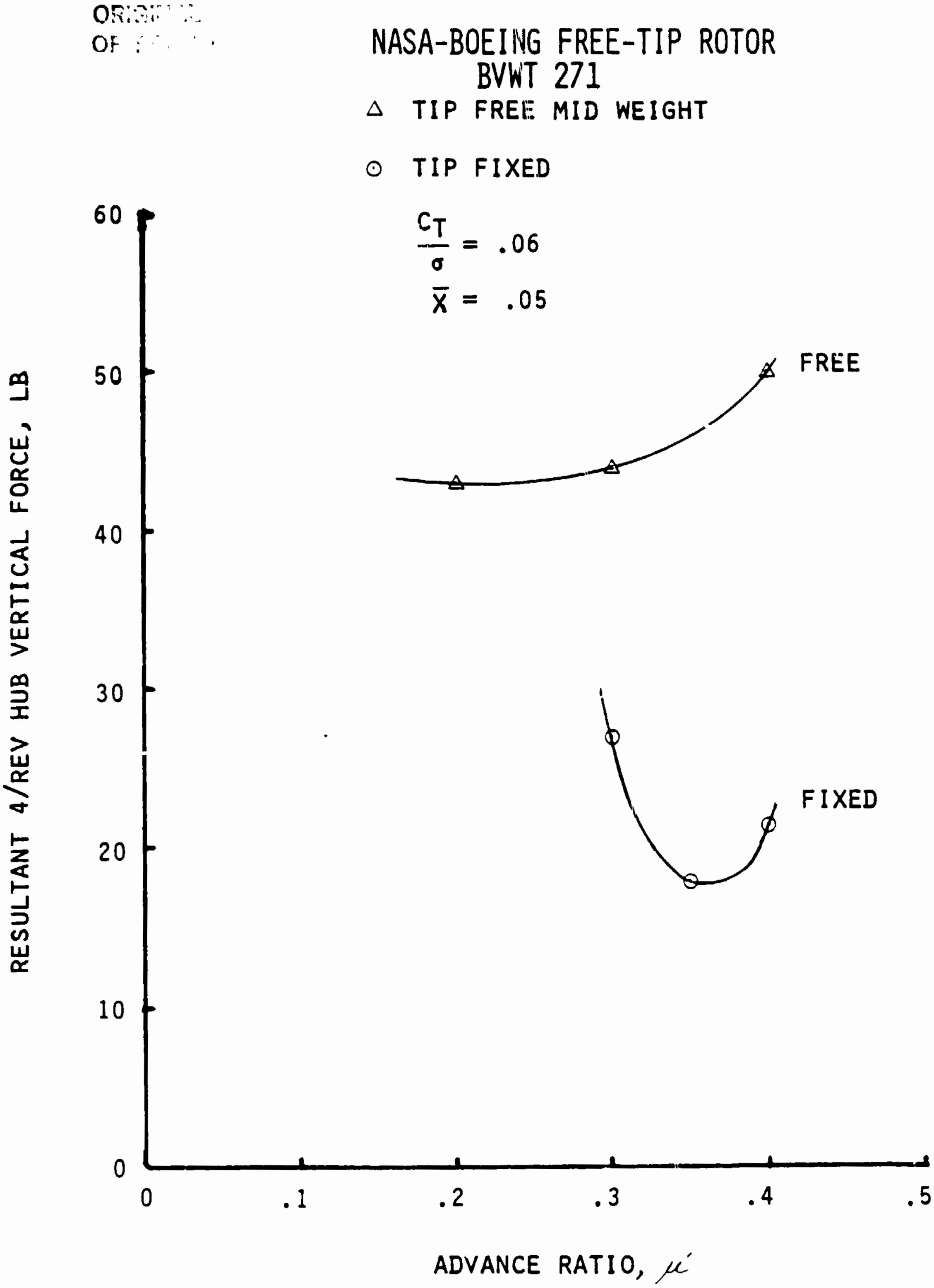

Figure 5.18 Comparison of Vertical Vibratory Hub Loads, Tip Fixed and Free

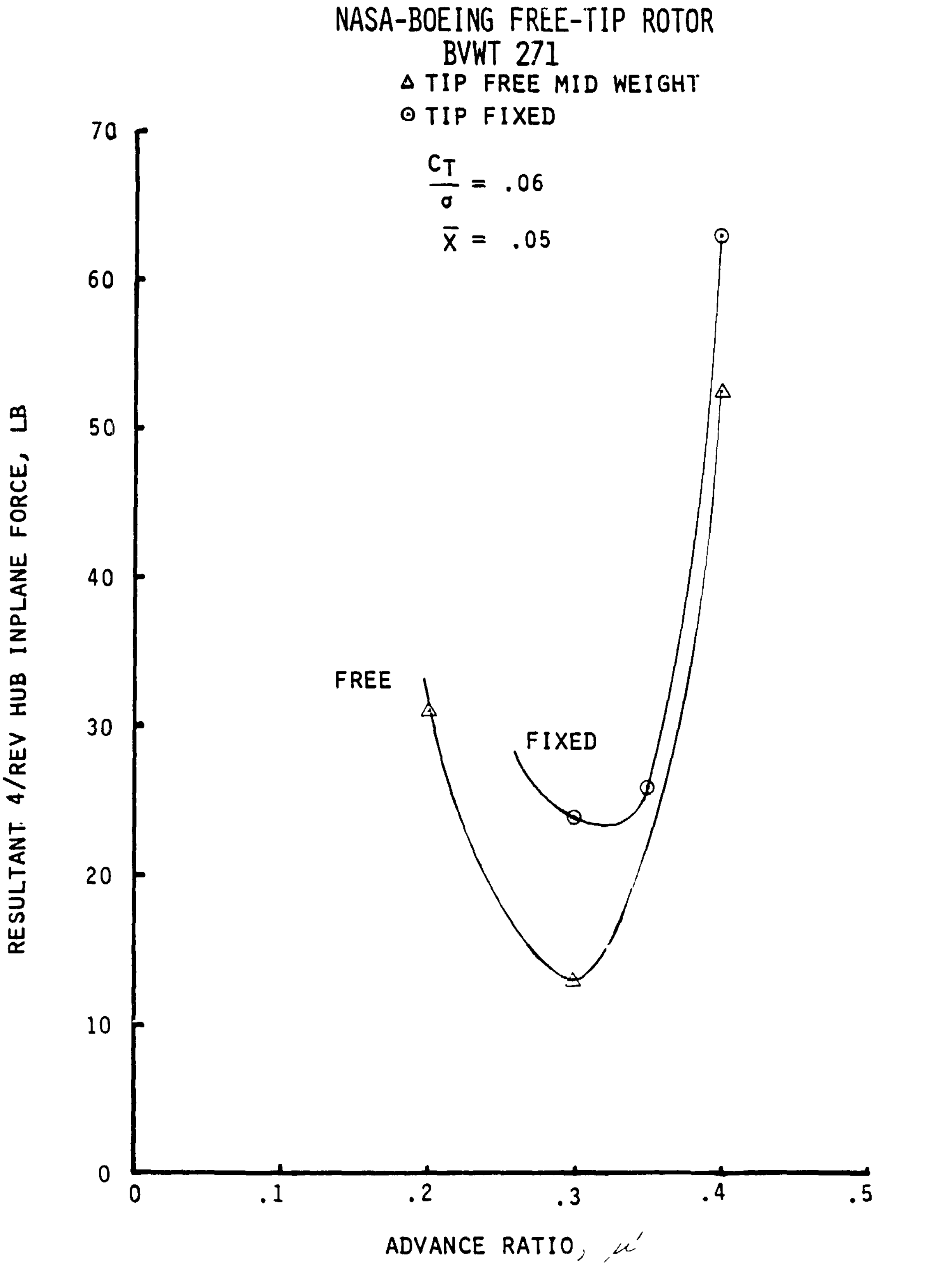

Figure 5.19 Comparison of the Inplane Vibratory Hub Loads, Tip Fixed and Free

center was assumed to lie on the quarter chord line. Based on these conditions, an effective angle of attack at the blade tip of 4° would be expected in hover at 681 ft/sec tip speed. If the downwash velocity at the rotor is assumed to be given by the momentum result

$$\frac{v_i}{V_T} = k\sqrt{\frac{C_T}{2}}$$

and the collective by

$$\theta_{.75} = k\sqrt{\frac{C_T}{2}} + \frac{6C_T}{\sigma a}$$

then the expected variation of tip angle with rotor thrust coefficient would be as shown in Figure 5.6. The calculated levels are considerably less than those measured.

The main reason for the discrepancy between the expected and actual tip angles is that the tip lift-curve slope was overestimated. The use of 5.73/rad for the overall lift-curve slope implies that the tip is part of a very high aspect ratio wing with a uniform lift distribution. This overlooks the drop-off in lift distribution at the blade tip and does not address the tendency of the tip to behave as a low aspect ratio surface, as illustrated in Figure 5.20. It would be expected, therefore, that the tip lift-curve slope would fall considerably below the two-dimensional value used in the design, and that the aerodynamic center position would move away from the quarter-chord point toward the leading edge. The variation of lift-curve slope and aerodynamic center position with aspect ratio is shown in Figures 5.7 and 5.8 and is taken from Reference 3. The combination of these effects would tend to increase the tip angle to the levels observed. With the tip operating at high angles of attack, the induced and profile drag would be greatly increased, resulting in much greater power requirements.

The tendency for the tip to operate at high angles could have been reduced by lowering the moment applied by the controller. However, no means was available for adjusting the controller moment. This would be a desirable feature in future designs.

In summary, the results of the test indicate that the free tip was operating at angles of attack well beyond those intended in the design. This is attributed to the lowered lift-curve slope and forward movement of the aerodynamic center on the low aspect ratio tip. The high angles of attack gave rise to high tip drag and reduced performance.

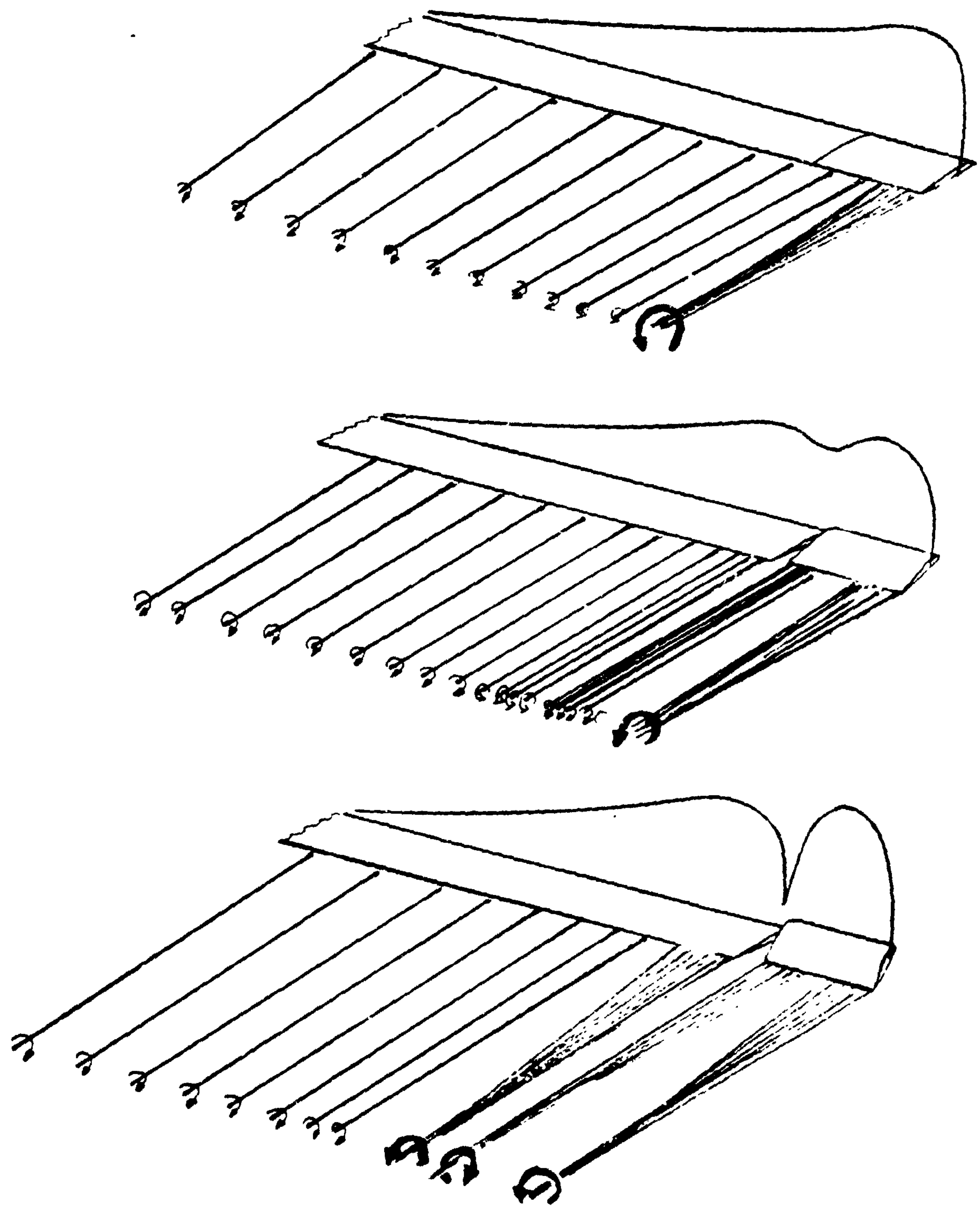

Figure 5.20 Development of Low Aspect Ratio Flow at Free Tip

6.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A wind tunnel test of a 16.8 ft. diameter free tip rotor was conducted in hover and in forward flight up to an advance ratio of 0.4. Based on the test results and analysis, the following conclusions are drawn:

1. The measured operating angle of the free tip was much greater than that anticipated during the design phase. This is the primary cause of the performance degradation.
2. Model hover performance was reduced when operating the rotor with the tip free, compared to that with the tip fixed.
3. The model power required in forward flight with the tip free was greater than that measured with the tip fixed at all advance ratios tested, when both rotors are operating at the same lift and propulsive force.
4. The large operating angle of the free tip is attributed to low aspect-ratio tip effects which reduce the tip lift effectiveness, increase the tip induced drag and move the aerodynamic center forward. The magnitude of these effects was not fully known when the tip was designed.
5. Hub 4/rev vertical loads were increased when the tips were free compared to the tip-fixed loads measured at the same operating condition.
6. Hub 4/rev in-plane loads were reduced with the tip free compared to the tip-fixed loads measured at the same operating condition.

Recommendations

Research should be directed toward understanding the complex, low aspect ratio flow conditions existing on the free tip. When these low aspect ratio tip aerodynamics are understood, this knowledge can be used to design a free tip rotor that will demonstrate the full potential of the concept. This research effort is best approached by a combination of analytical modeling and wind tunnel testing. Specifically, it is recommended that:

1. A wind tunnel test should be conducted using nonrotating, semispan models of the free tip. The test would gather data on the tip lift, drag, and pitching moment characteristics over the full operating Mach number range at combinations of main blade and free tip angles of attack. Various tip spans would also be tested to measure the effect of tip aspect ratio on the aerodynamic characteristics.

2. In parallel with the wind tunnel test, a detailed analytical model of a free tip rotor should be developed with attention being focused on representing the low aspect ratio tip effects. The model would make extensive use of the data obtained from the wind tunnel test.

3. When the analytical model is completed and verified, it should be used to design a free tip rotor that will provide improved performance and reduced vibratory loads.

4. An alternate means should be explored for providing the tip controlling moment.

7.0 REFERENCES

1. Stroub, Robert: Performance Improvements with the Free Tip Rotor; AHS National Specialists' Meeting on Rotor System Design, Philadelphia, October 1980.

2. Silcox, H. and Rosenstein, H.: Feasibility Study of a Constant Lift Rotor Tip; Boeing Vertol Report D210-11704-1, 30 July 1980.

3. Flax, A. H. and Lawrence, H.R. The Aerodynamics of Low Aspect-Ratio Wings and Wing-Body Combinations. Cornell Aeronautical Laboratory Report, CAL-37, 1951.

APPENDIX A. TEST DATA

Presented in this Appendix are the basic data plots for all the free tip rotor configurations tested. The data is corrected for hub tares. No corrections were applied for wall effects because the test was conducted with the working-section slots open, a configuration that yields essentially free-air conditions. The rotor advance ratios and free-tip configurations tested, together with the page number where the data is presented, are shown in the table below.

μ	FIXED, LIGHT WEIGHT	FREE, MID WEIGHT	FREE, LIGHT WEIGHT	FREE, EXTRA LIGHT WEIGHT	FREE, NO WEIGHTS
0	-	-	A-4	-	-
.20	-	A-45	-	-	-
.30	A-11	A-56	A-89	A-111	A-144
.35	A-21	A-67	A-100	A-122	A-155
.40	A-31	A-78	-	A-133	A-166

The terms light weight, mid weight, etc., refer to the number and arrangement of the tip weights. These are shown in Table A-1.

The data plots are presented in the following order:

<u>Hover</u>

C_T/σ vs. C_P/σ

FM vs. C_T/σ

$\theta_{.75}$ vs. C_T/σ

δ vs. C_T/σ

C_P/σ vs. $M_{1,90}$

C_T/σ vs. $M_{1,90}$

δ vs. $M_{1,90}$

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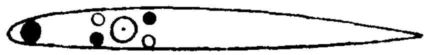
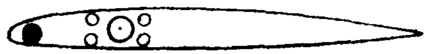
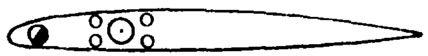
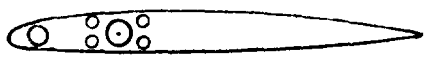
CONDITION	ARRANGEMENT OF WEIGHTS	TIP WEIGHT (LB)	TIP INERTIA ABOUT PIVOT (SLUG FT^2)
MID WEIGHT		0.501	3.88×10^{-5}
LIGHT WEIGHT		0.341	3.24×10^{-5}
EXTRA LIGHT WEIGHT		0.255	2.5×10^{-5}
NO WEIGHTS		0.i69	1.758×10^{-5}

Table A-1 Tip Configuration, Weights, and Inertias

Forward Flight

*C_P/σ vs. $M_{1,90}$

*C_T'/σ vs. $M_{1,90}$

*L/D_E vs. $M_{1,90}$

*Resultant 4/rev Inplane Moment vs. $M_{1,90}$

C_T'/σ vs. C_P/σ

L/D_E vs. C_T'/σ

$\bar{X}$ vs. C_T'/σ

A_{1C} vs. C_T'/σ

B_{1C} vs. C_T'/σ

$\theta_{.75}$ vs. C_T'/σ

**δ vs. C_T'/σ

Resultant 4/rev Hub Vertical Force vs. C_T'/σ

Resultant 4/rev Hub Inplane Force vs. C_T'/σ

Alternating Blade Torsion at $x = .13$ vs. C_T'/σ

Resultant 4/rev Inplane Moment vs. C_T'/σ

*Presented only for tip fixed, light weight, $\mu = .4$
**Not presented for tip fixed, since $\delta = 0$

The definitions of the quantities presented in the plots are given on the following page.

LIST OF SYMBOLS FOR APPENDIX A

A	Rotor disc area, πR^2, ft^2
A_{1C}	Lateral cyclic pitch, degrees
B	Number of blades
B_{1C}	Longitudinal cyclic pitch, degrees
C_P	Rotor power coefficient, 550 $RHP/\rho A V_T{}^3$
C'_T	Rotor lift coefficient, $L/\rho A V_T{}^2$
c	Blade chord, ft.
D	Rotor diameter, ft.
D_E	Rotor effective drag, $\frac{550\ RHP}{V} - X$, lb
FM	Rotor figure of merit, $.707 C'_T{}^{3/2}/C_P$
L	Rotor lift, lb
$M_{1,90}$	Advancing blade tip Mach number
q	Free stream dynamic pressure, $\frac{1}{2}\rho V^2$
R	Blade radius, ft.
RHP	Rotor shaft horsepower
V	Tunnel speed, fps
V_T	Rotor tip speed, fps
X	Rotor propulsive force, lb
$\overline{X}$	Rotor propulsive force coefficient, $X/qD^2\sigma$
α_S	Rotor shaft angle, positive aft, degrees
δ	Angle of free tip relative to main blade (positive nose up)
$\theta_{.75}$	Blade collective pitch at .75R, degrees
μ	Rotor advance ratio, V/V_T
ρ	Air density slug/ft^3
σ	Rotor solidity, $Bc/\pi R$

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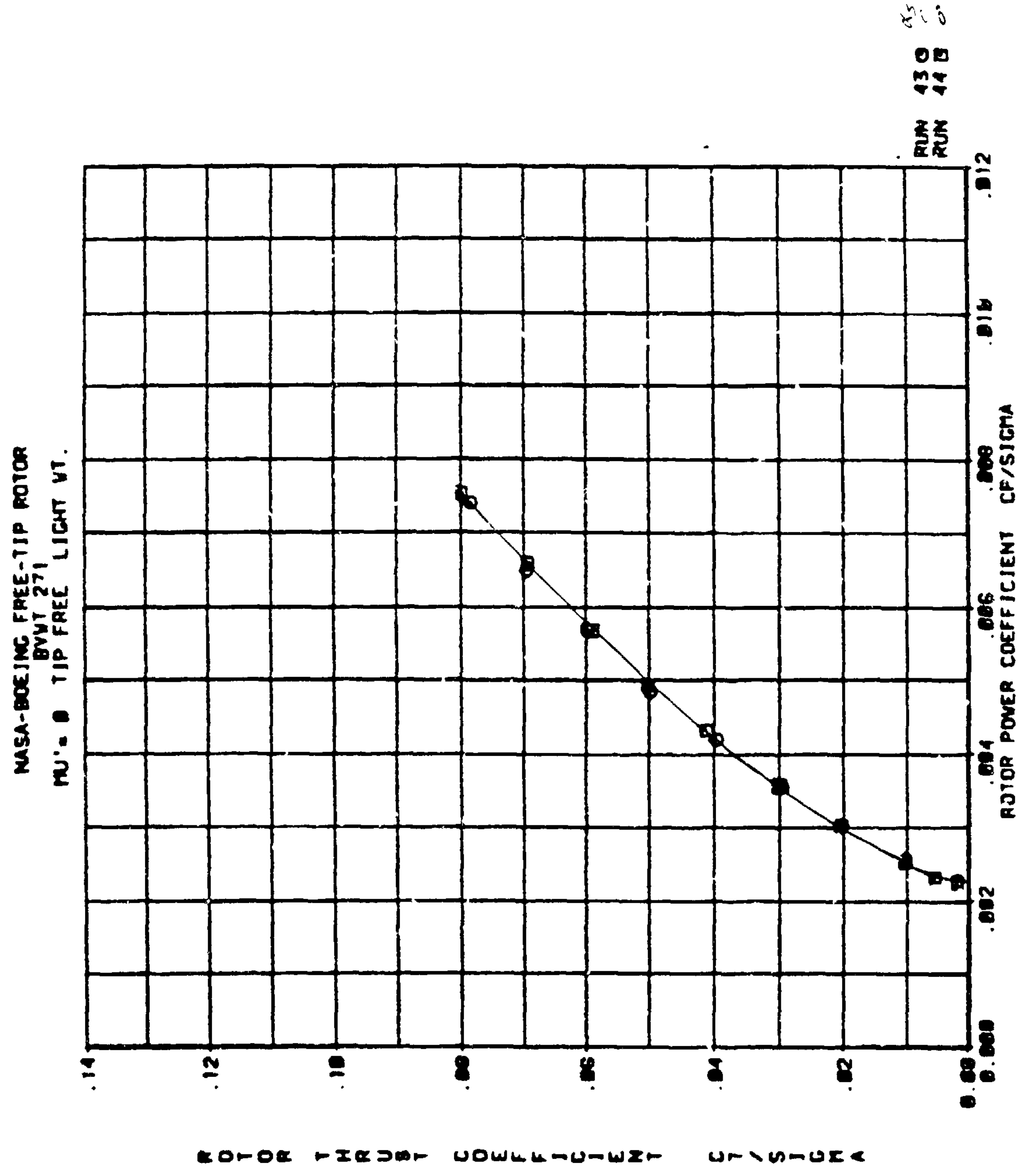

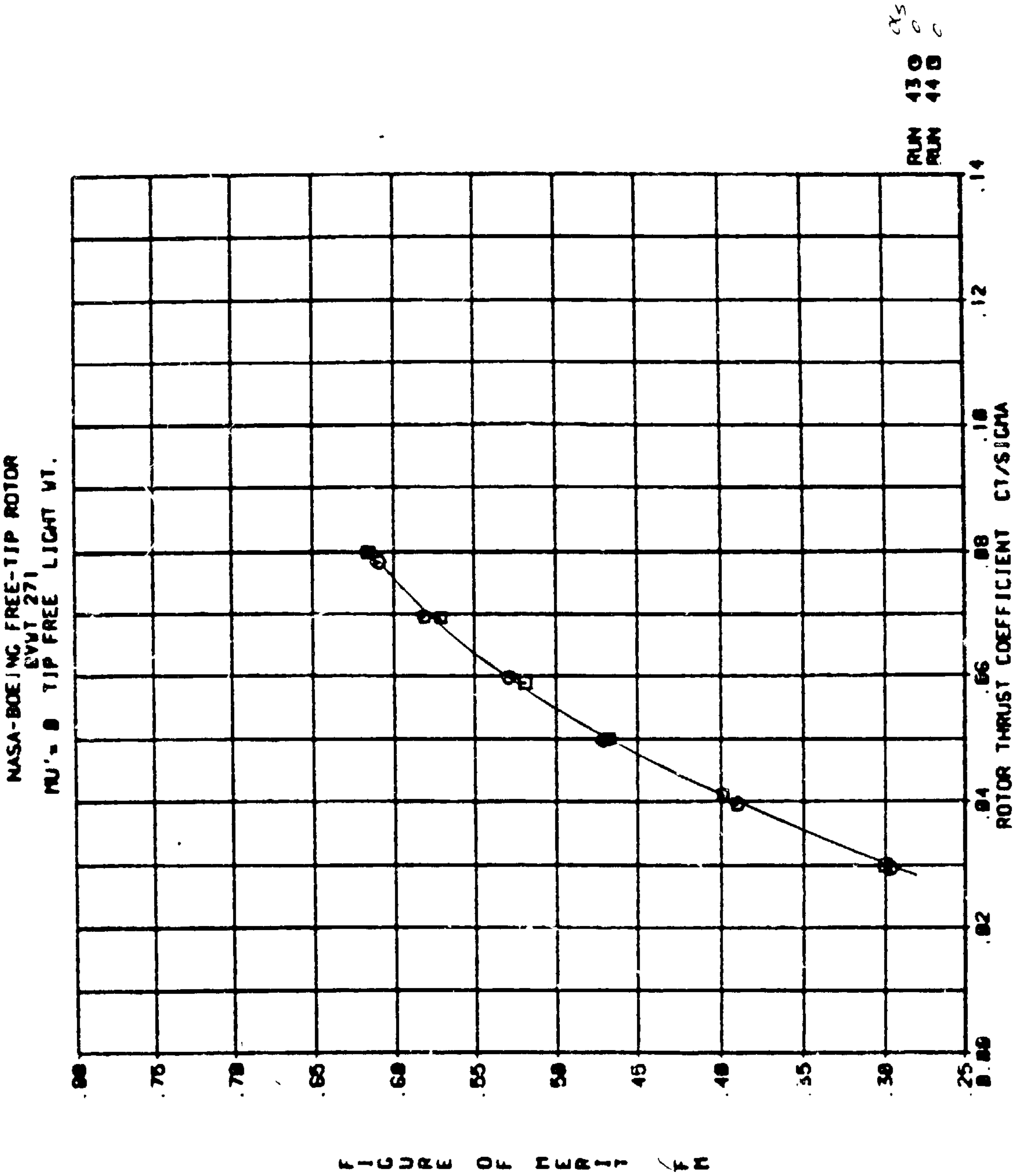
NASA-BOEING FREE-TIP ROTOR
EVWT 271
MU's 0 TIP FREE LIGHT WT.
ROTOR THRUST COEFFICIENT CT/SIGMA
RUN 43
RUN 44
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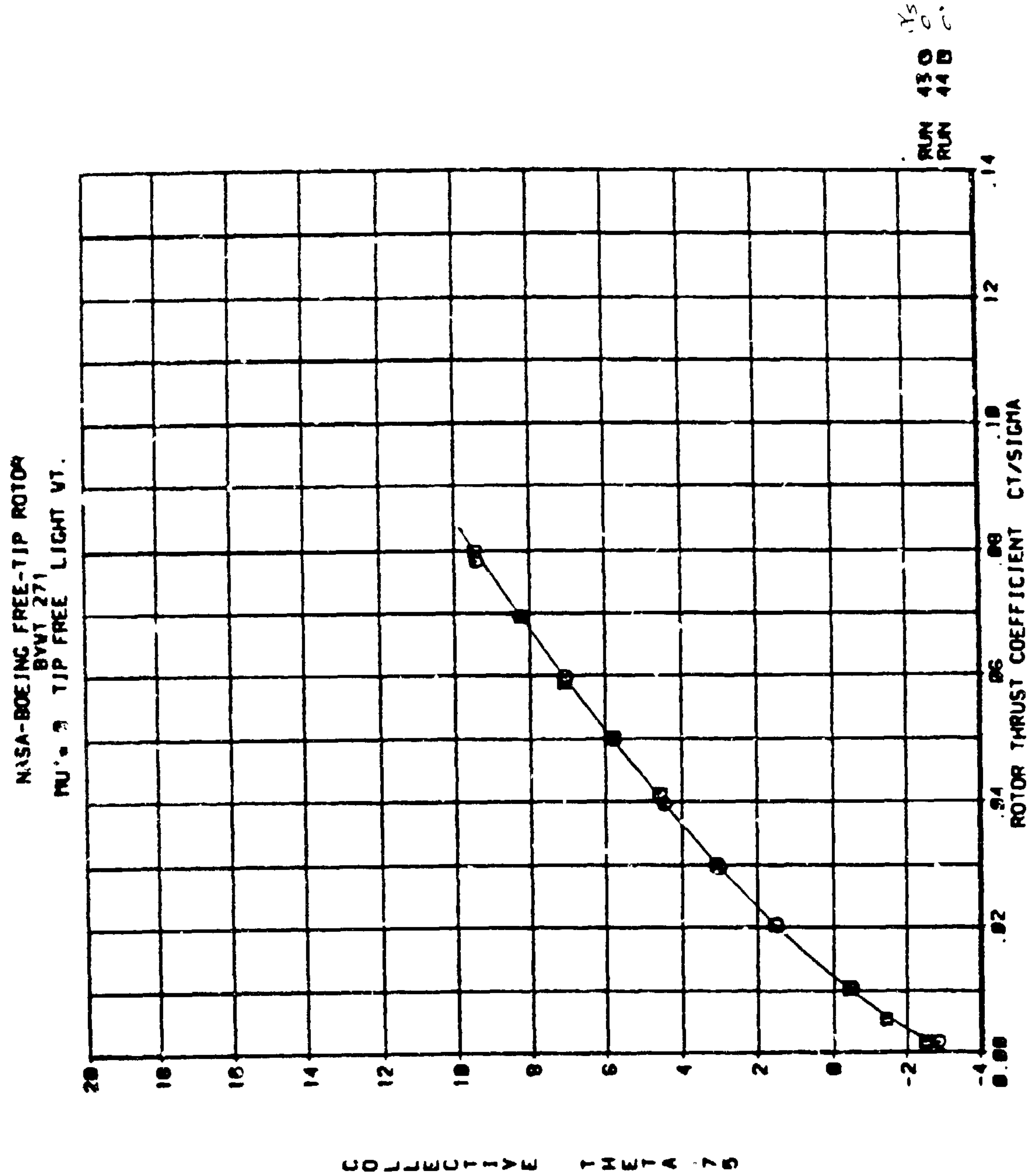
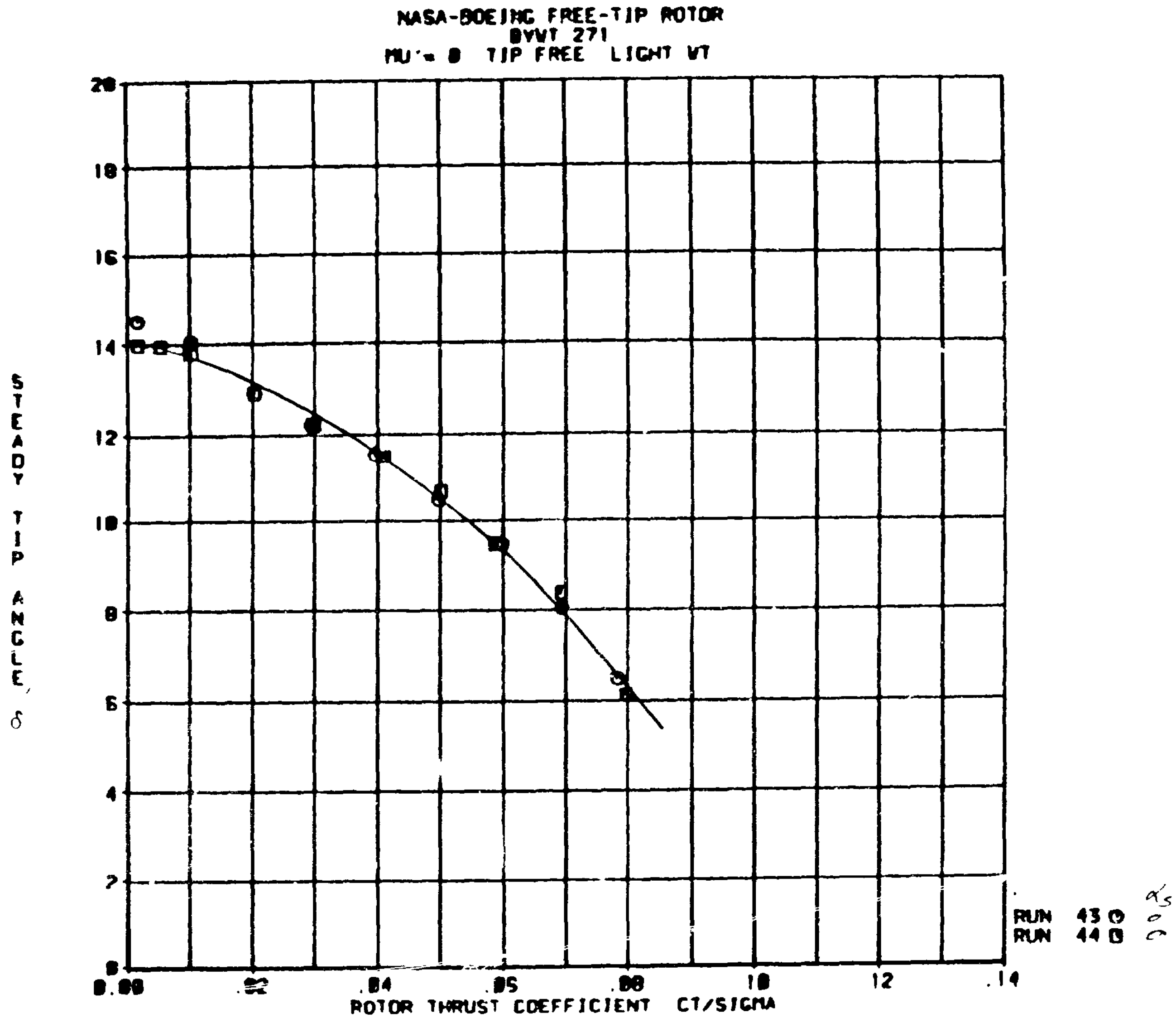
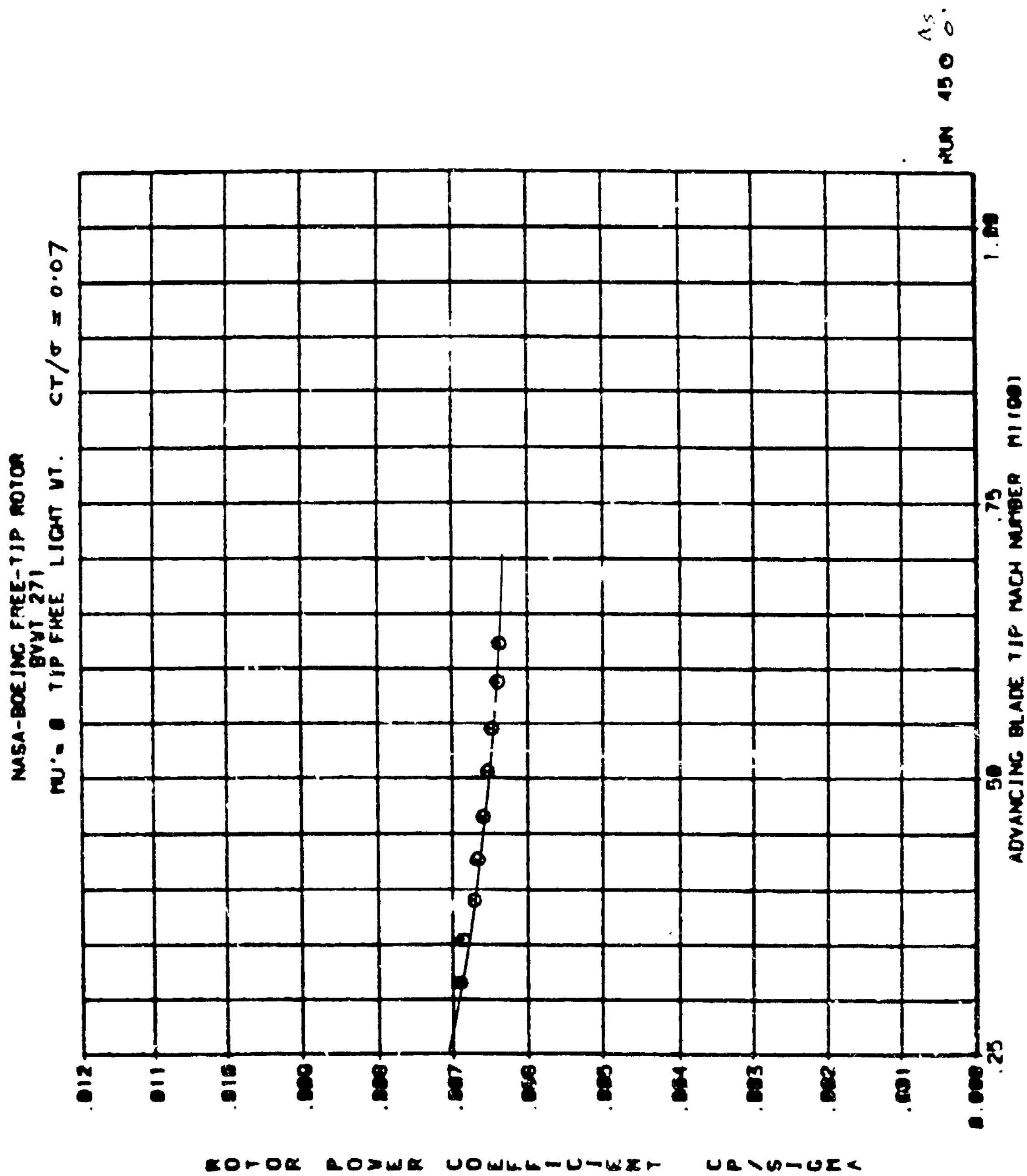
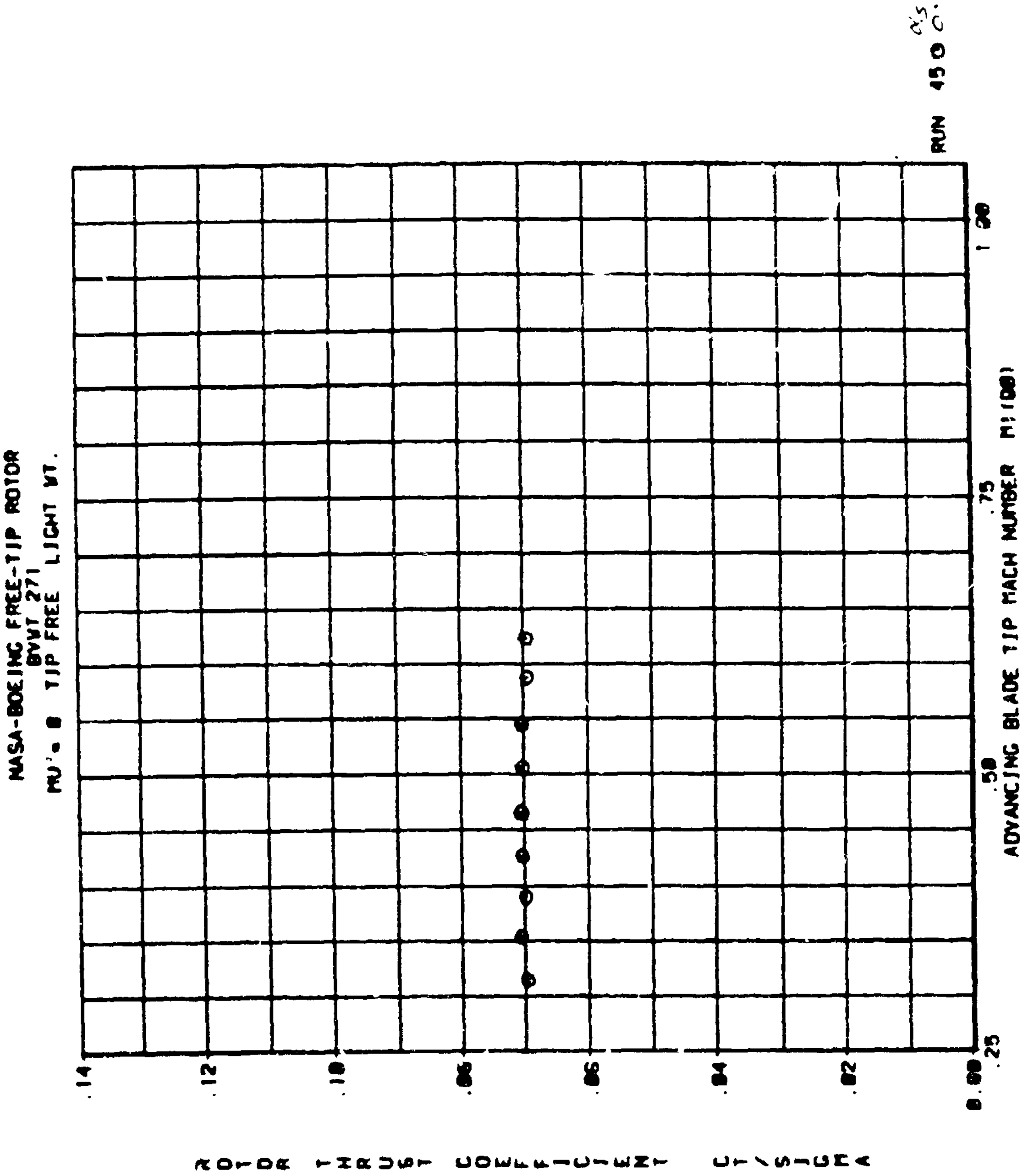
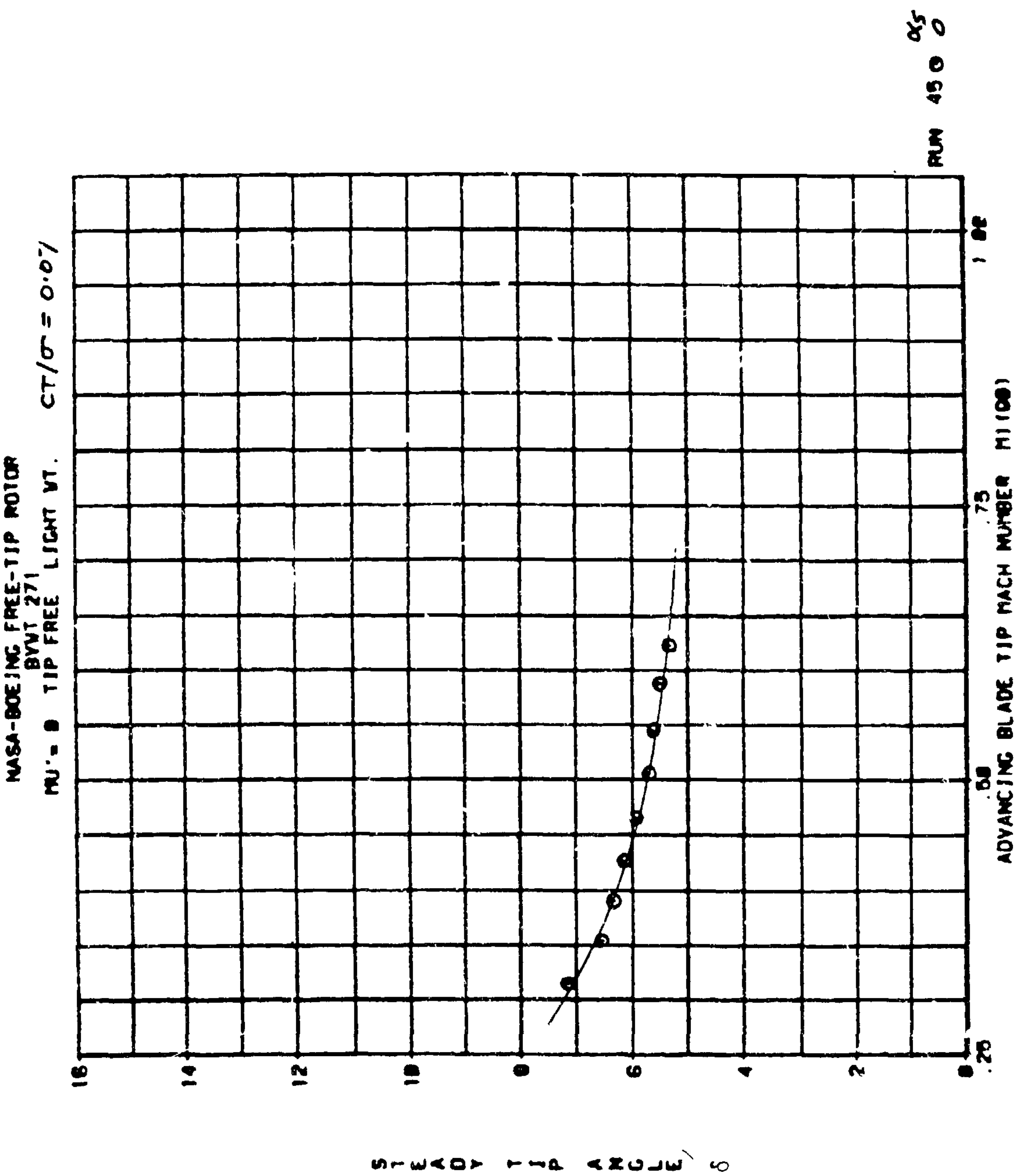


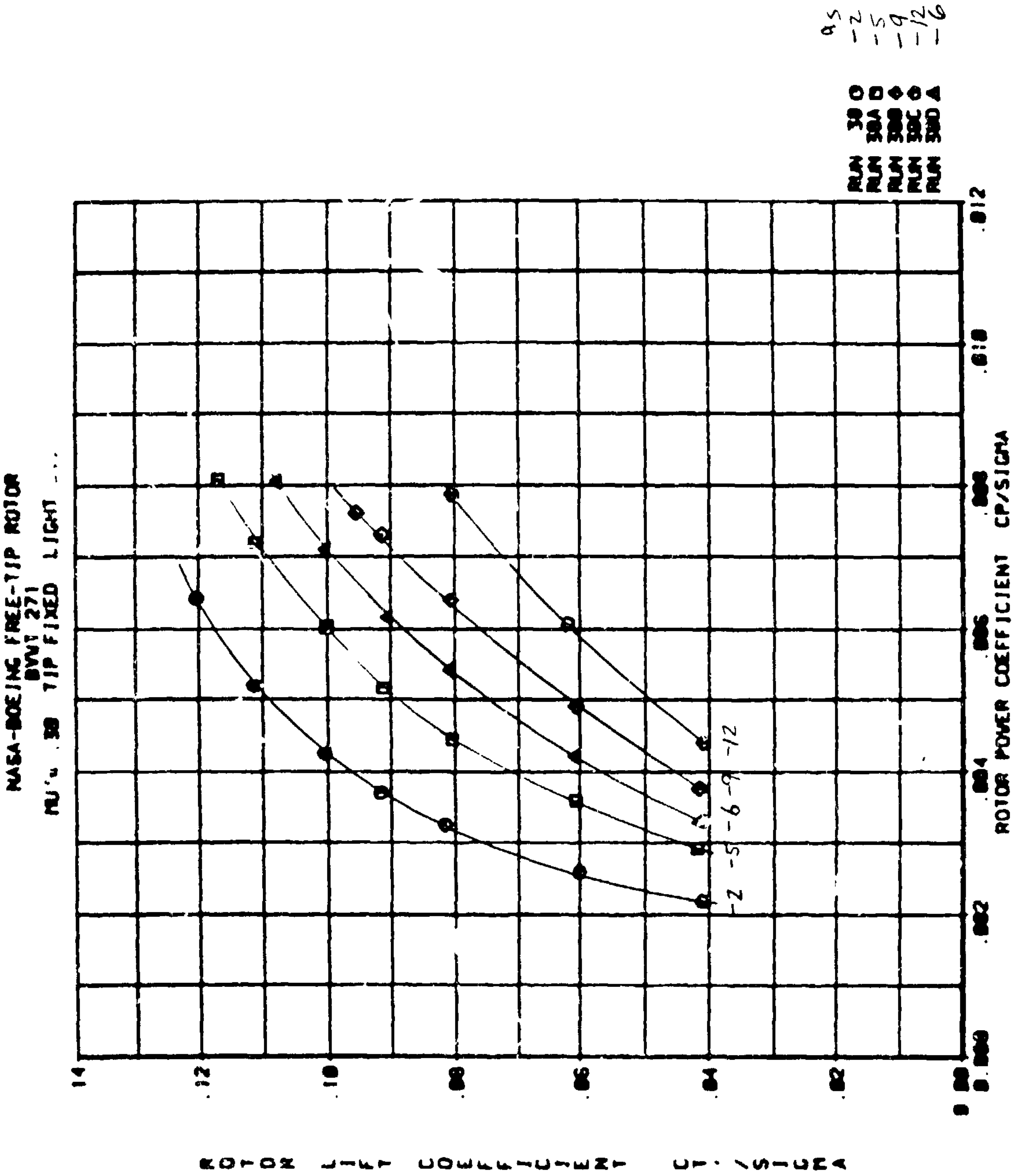


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU = 0 TIP FREE LIGHT WT
STEADY TIP ANGLE, δ
ROTOR THRUST COEFFICIENT CT/SIGMA
RUN 43 ○ α_s 0°
RUN 44 □ 0°
20
18
16
14
12
10
8
6
4
2
0
0.00
.02
.04
.06
.08
.10
12
.14


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= 0 TIP FREE LIGHT WT.
CT/σ = 0.07
RUN 450
ADVANCING BLADE TIP MACH NUMBER
.25
.50
.75
1.00
.007
.005
.004
.003
.002
.001
0.000


NASA-BOEING FREE-TIP ROTOR
BVWT 271
TIP FREE LIGHT WT.
RUN 45
ADVANCING BLADE TIP MACH NUMBER
.25
.50
.75
1.00
.14
.12
.10
.08
.06
.04
.02
0.00


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU = 0 TIP FREE LIGHT WT.
CT/σ = 0.07
RUN 45 ⊙ αS 0
ADVANCING BLADE TIP MACH NUMBER M1(90)
.25
.50
.75
1.00
0
2
4
6
8
10
12
14
16
STEADY TIP ANGLE δ


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU = .38 TIP FIXED LIGHT
RUN 38 -2
RUN 38A -5
RUN 38B -9
RUN 38C -12
RUN 38D -6
ROTOR POWER COEFFICIENT CP/SIGMA
-2 -5 -6 -9 -12
.14
.12
.10
.08
.06
.04
.02
0.000
.002
.004
.006
.008
.010
.012

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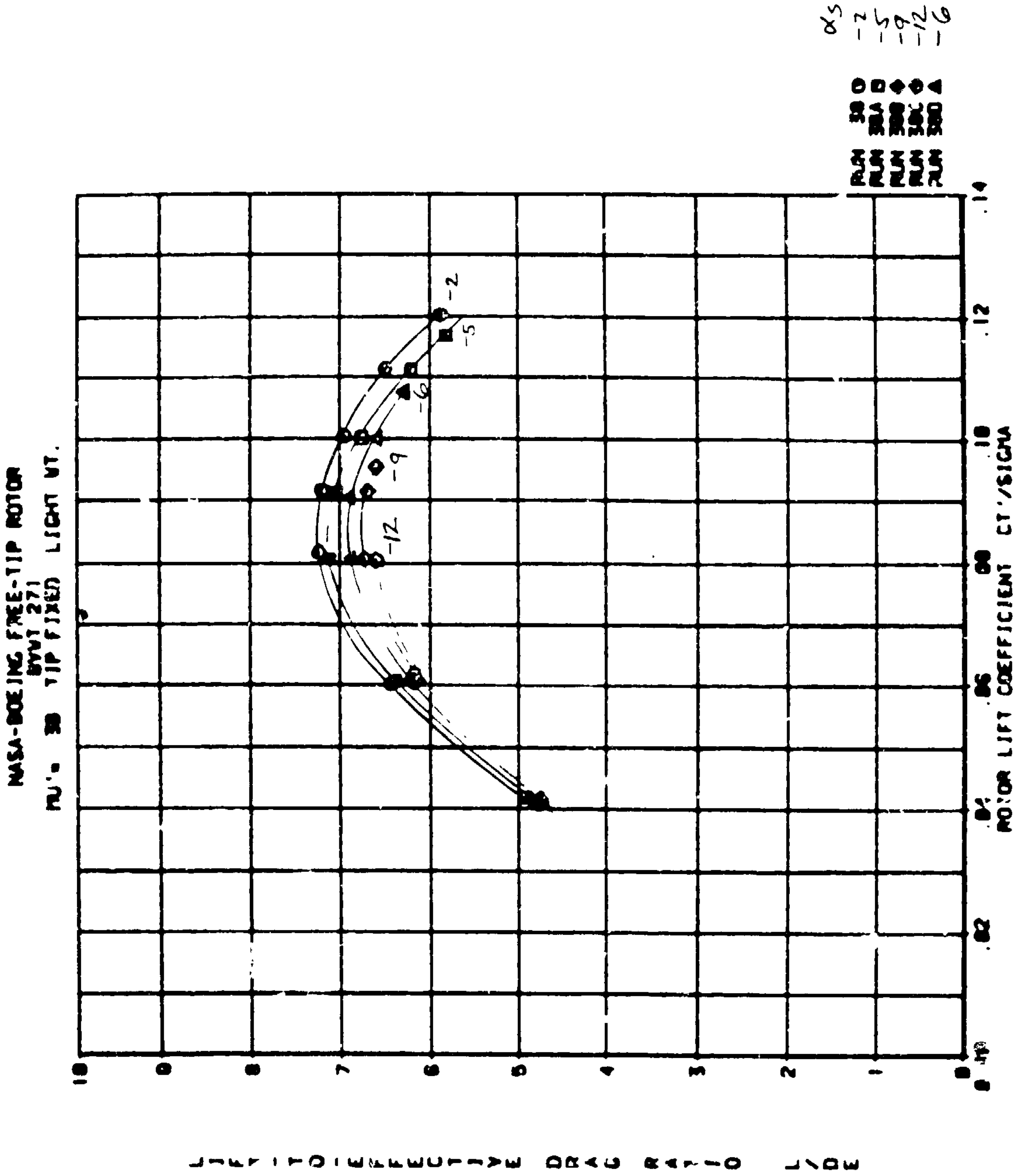

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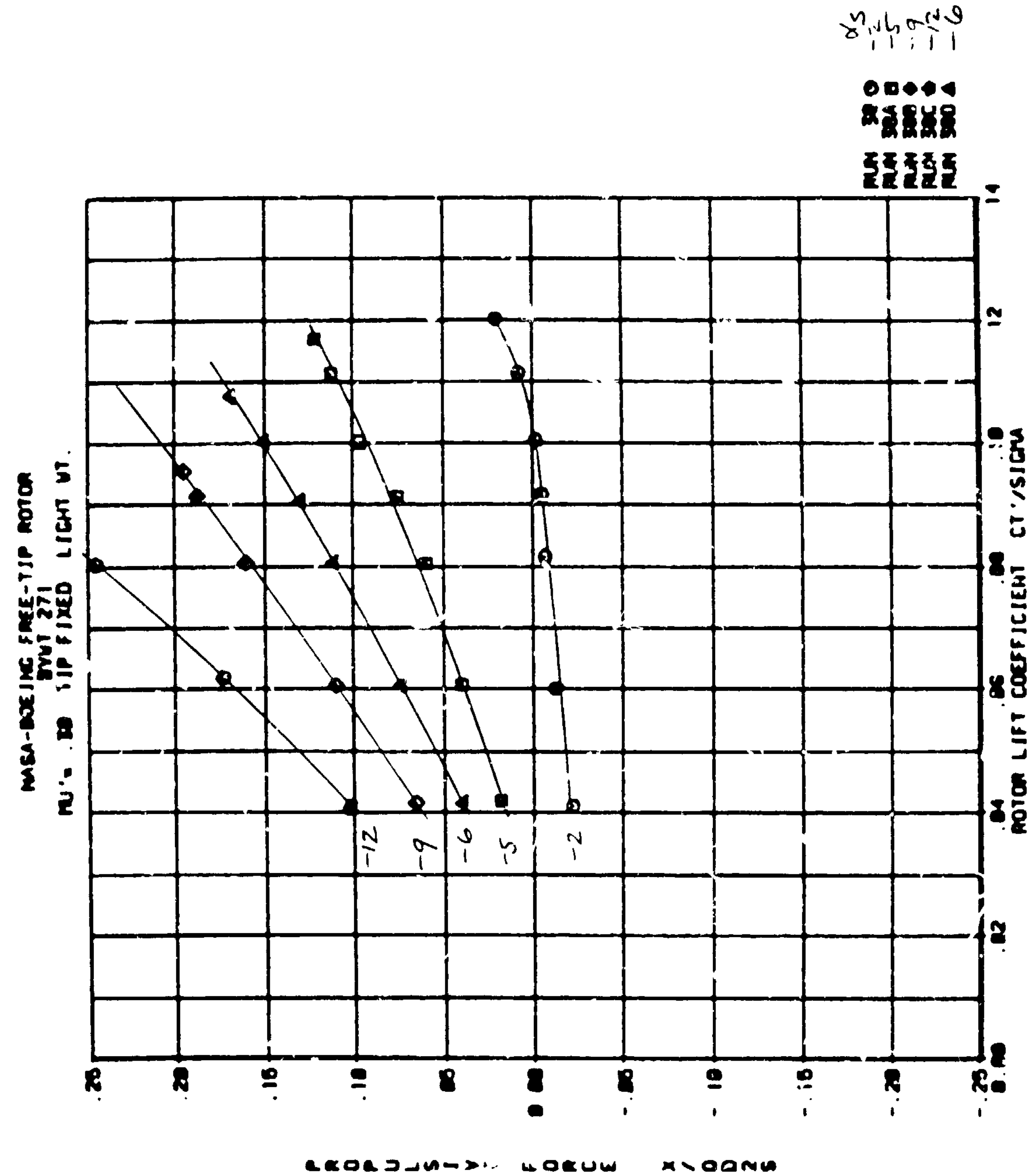

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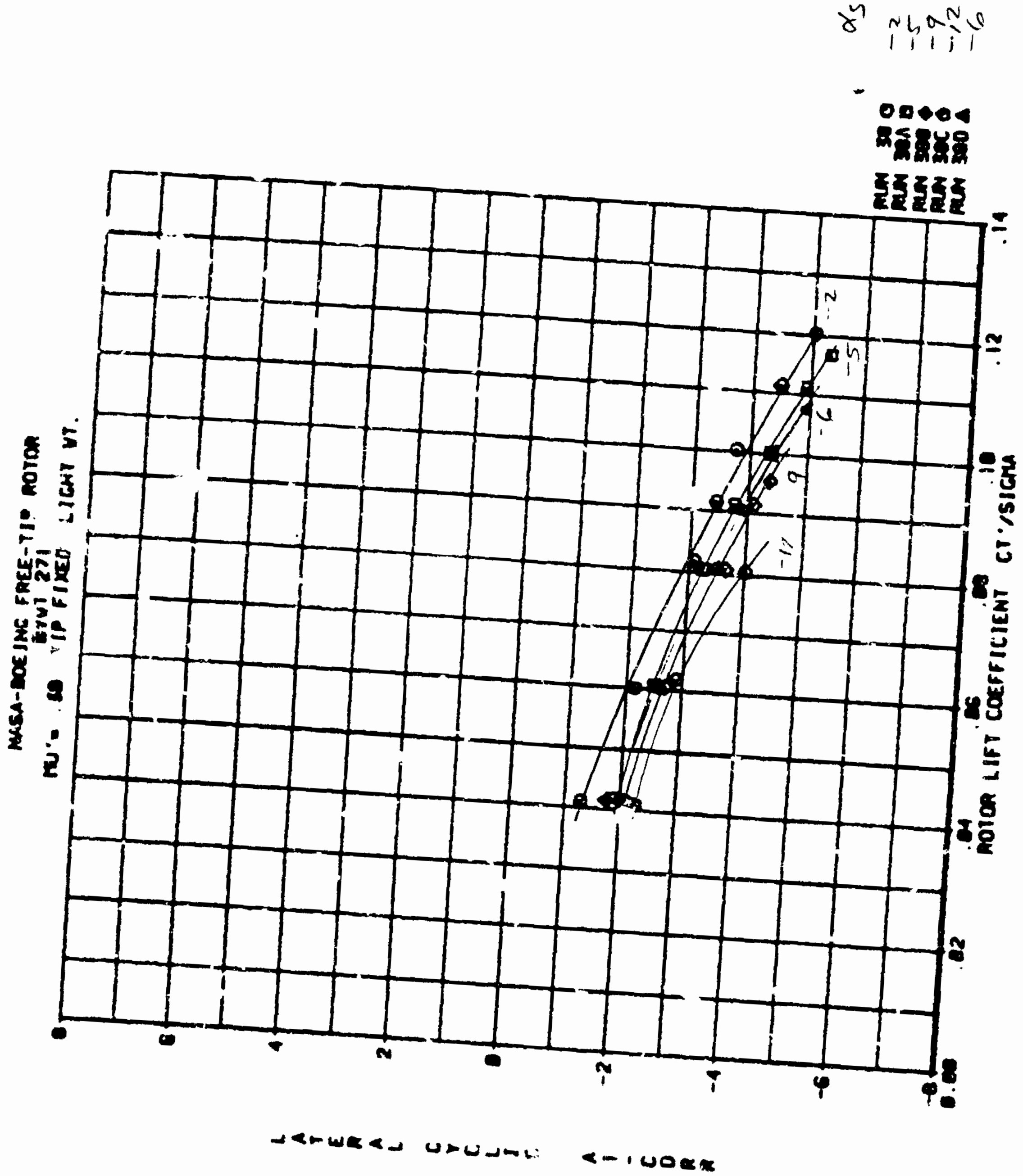
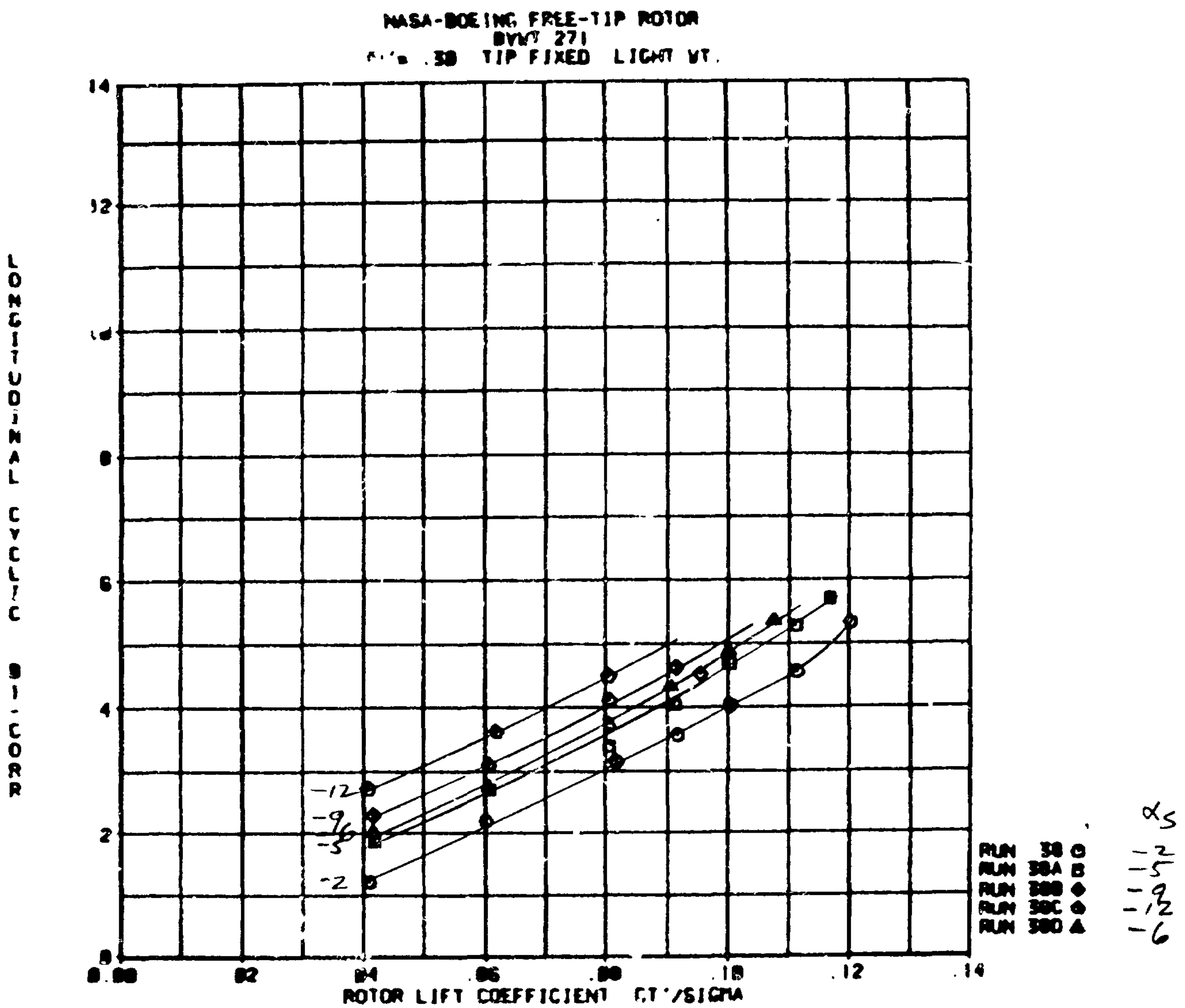
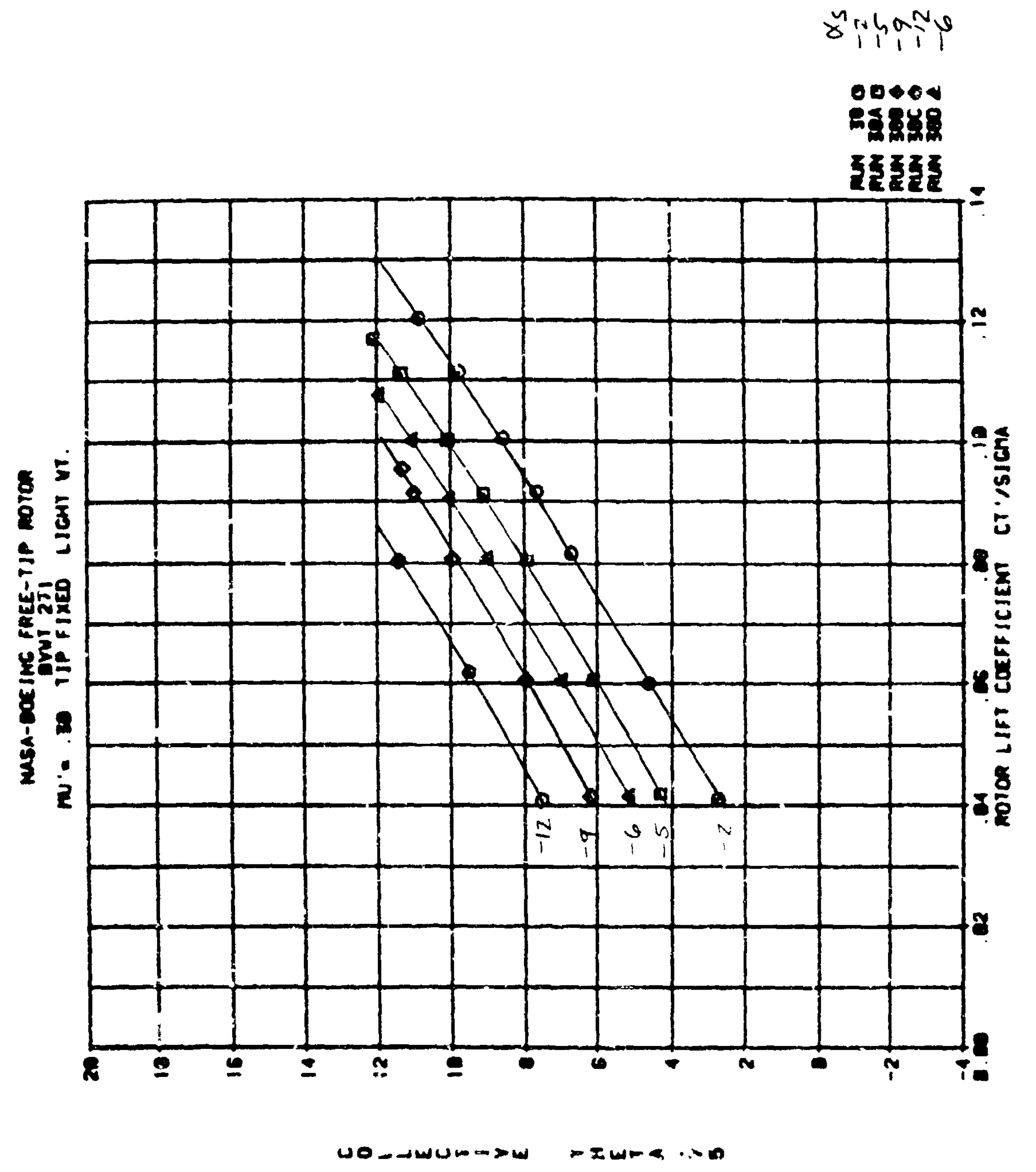


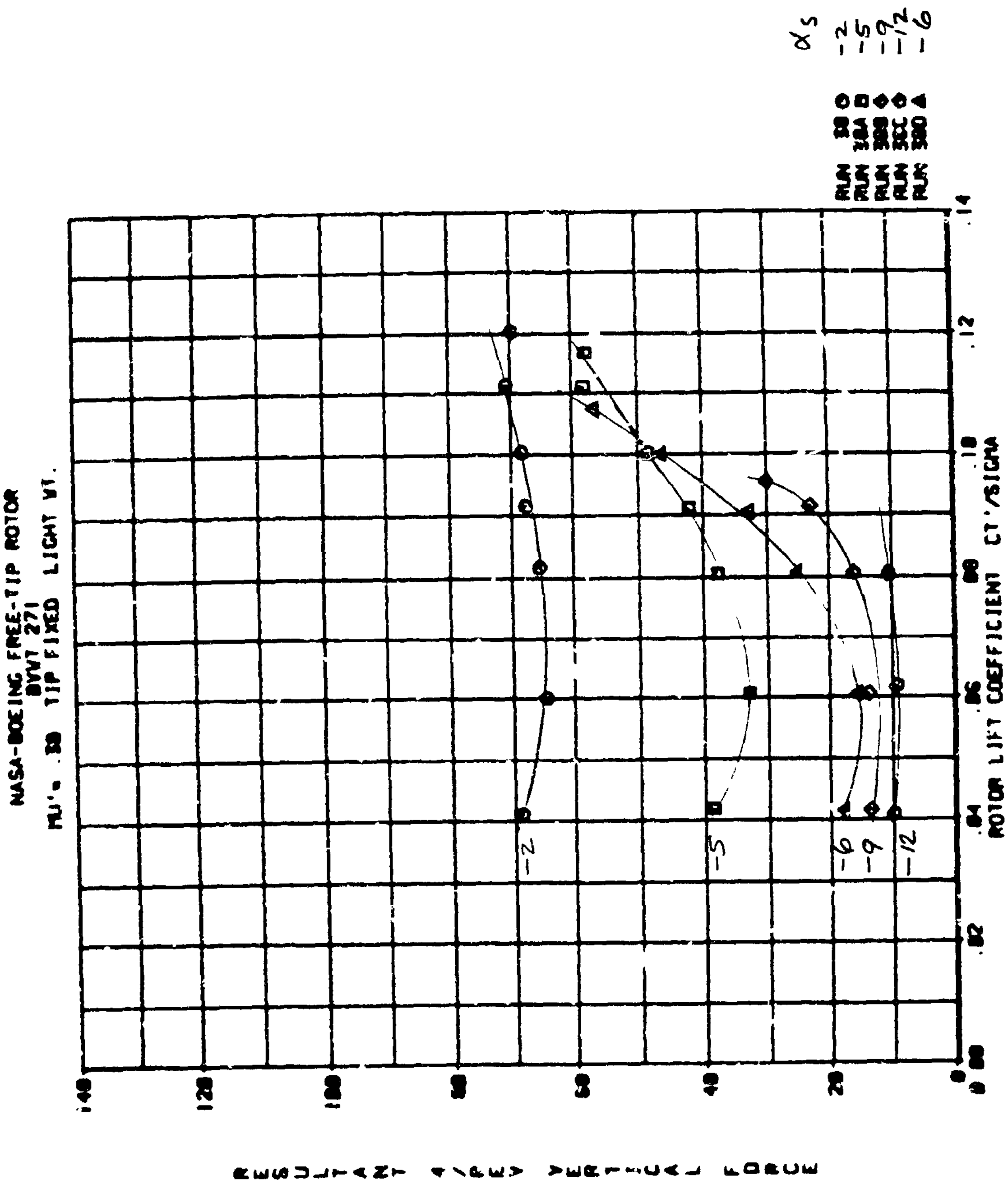


NASA-BOEING FREE-TIP ROTOR
BVWT 271
.30 TIP FIXED LIGHT WT.
LONGITUDINAL CYCLIC B1-CORR
ROTOR LIFT COEFFICIENT CT'/SIGMA
RUN 38 -2
RUN 38A -5
RUN 38B -9
RUN 38C -12
RUN 38D -6
α_S

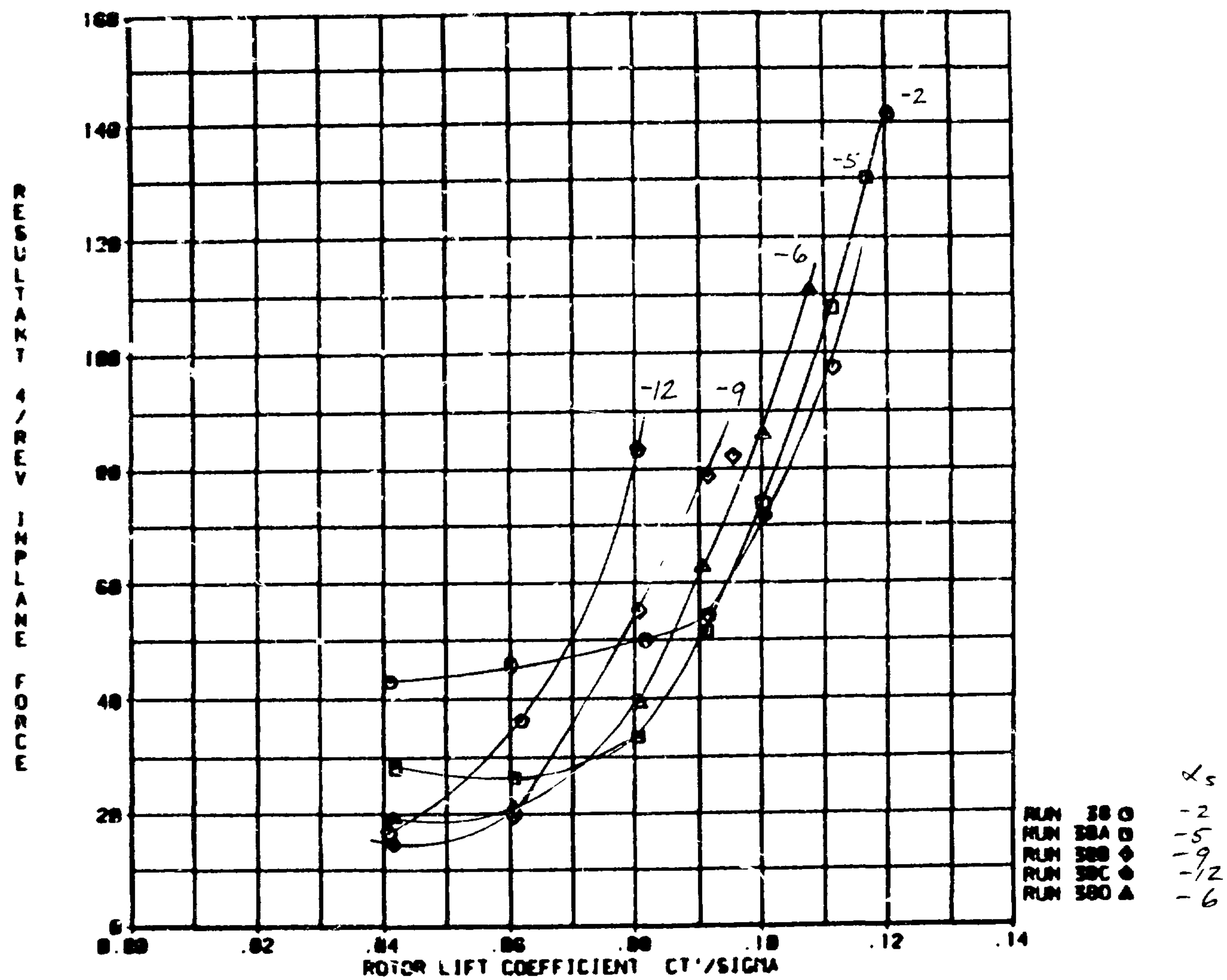
ORIGINAL
OF



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .30 TIP FIXED LIGHT WT.
RUN 30
RUN 30A
RUN 30B
RUN 30C
RUN 30D
αs
-2
-5
-9
-12
-6
ROTOR LIFT COEFFICIENT CT'/SIGMA
-12
-9
-6
-5
-2


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .30 TIP FIXED LIGHT WT.
ROTOR LIFT COEFFICIENT CT'/SIGMA
α_S
-2
-5
-9
-12
-6

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .38 TIP FIXED LIGHT WT.



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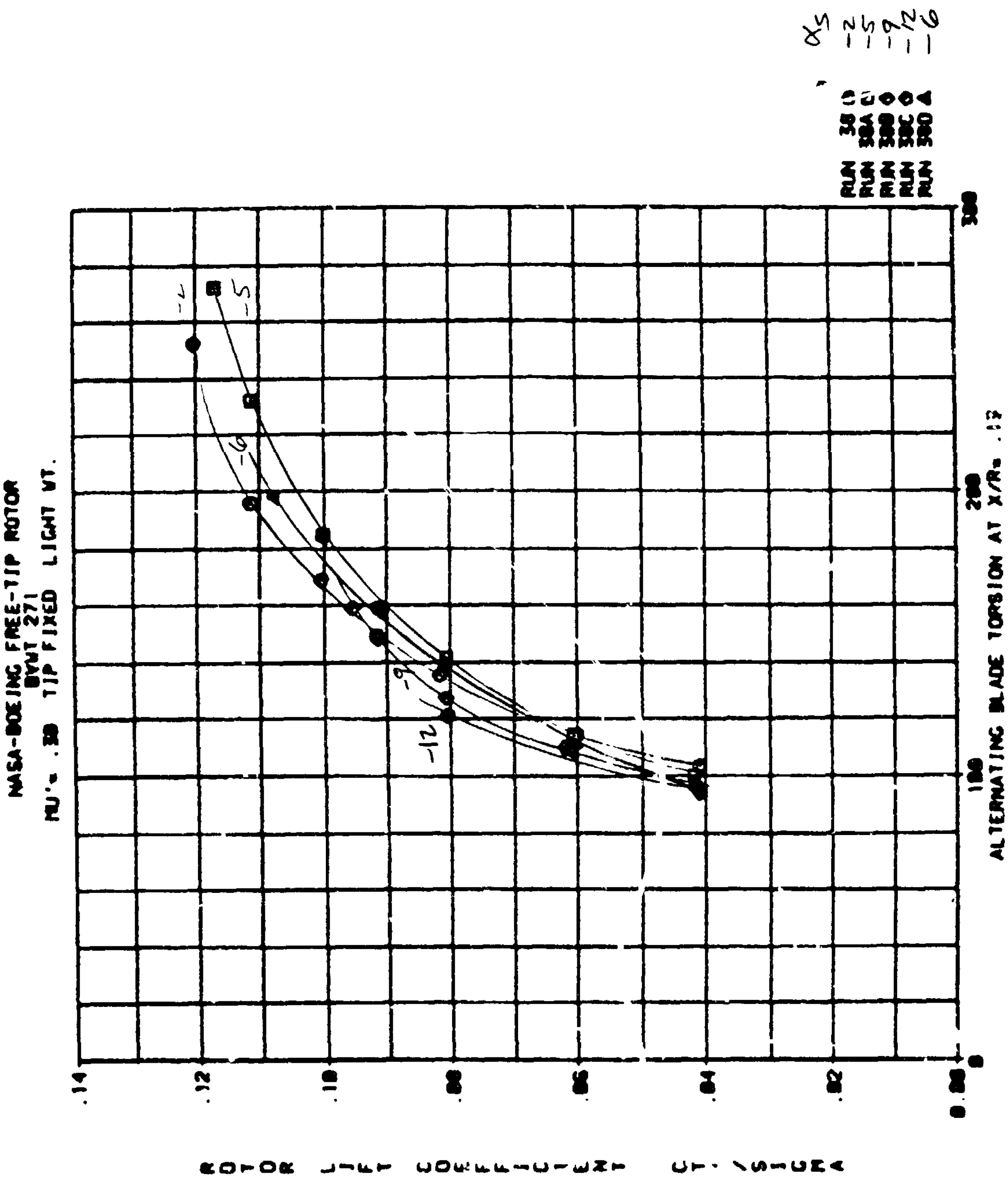
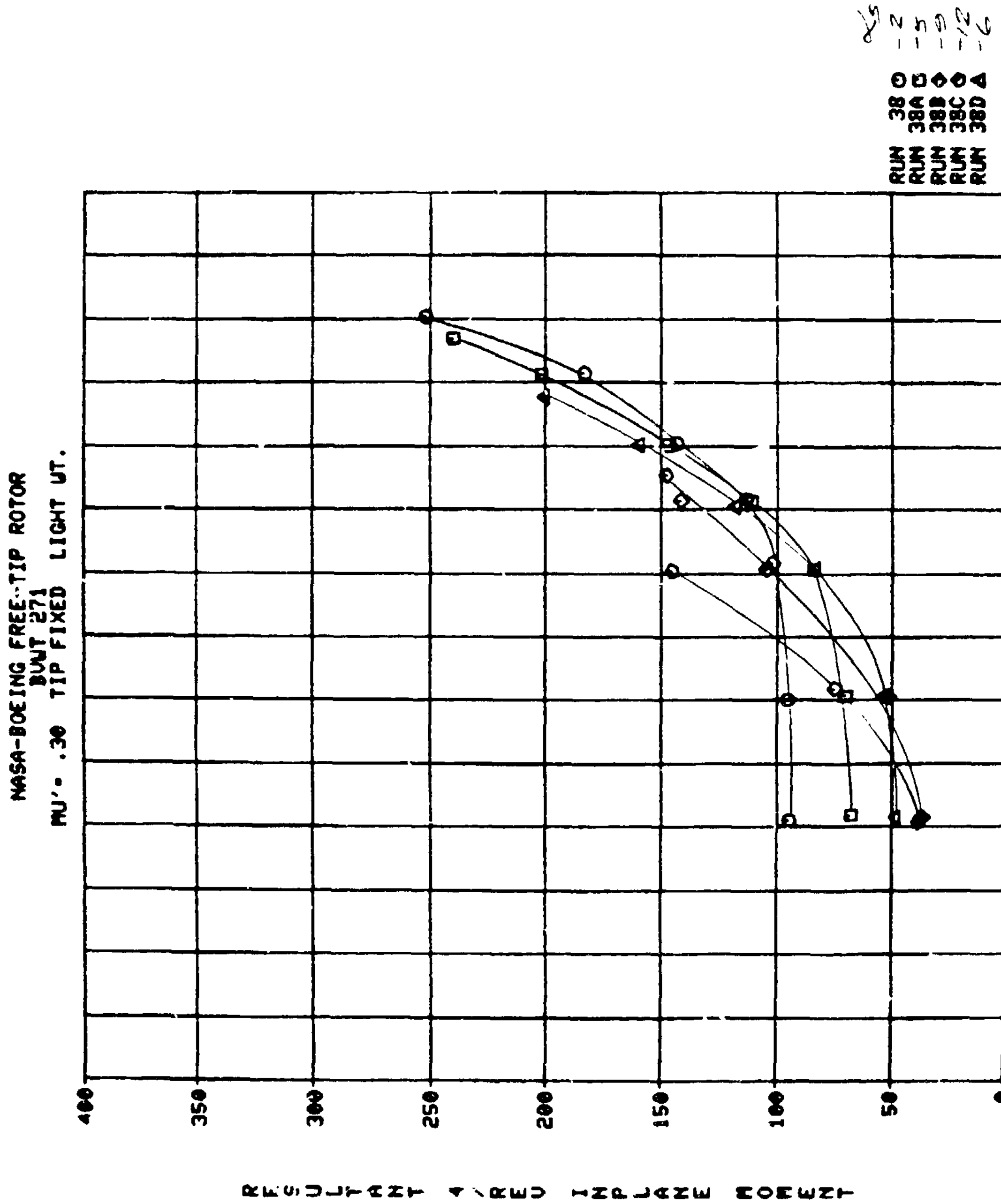
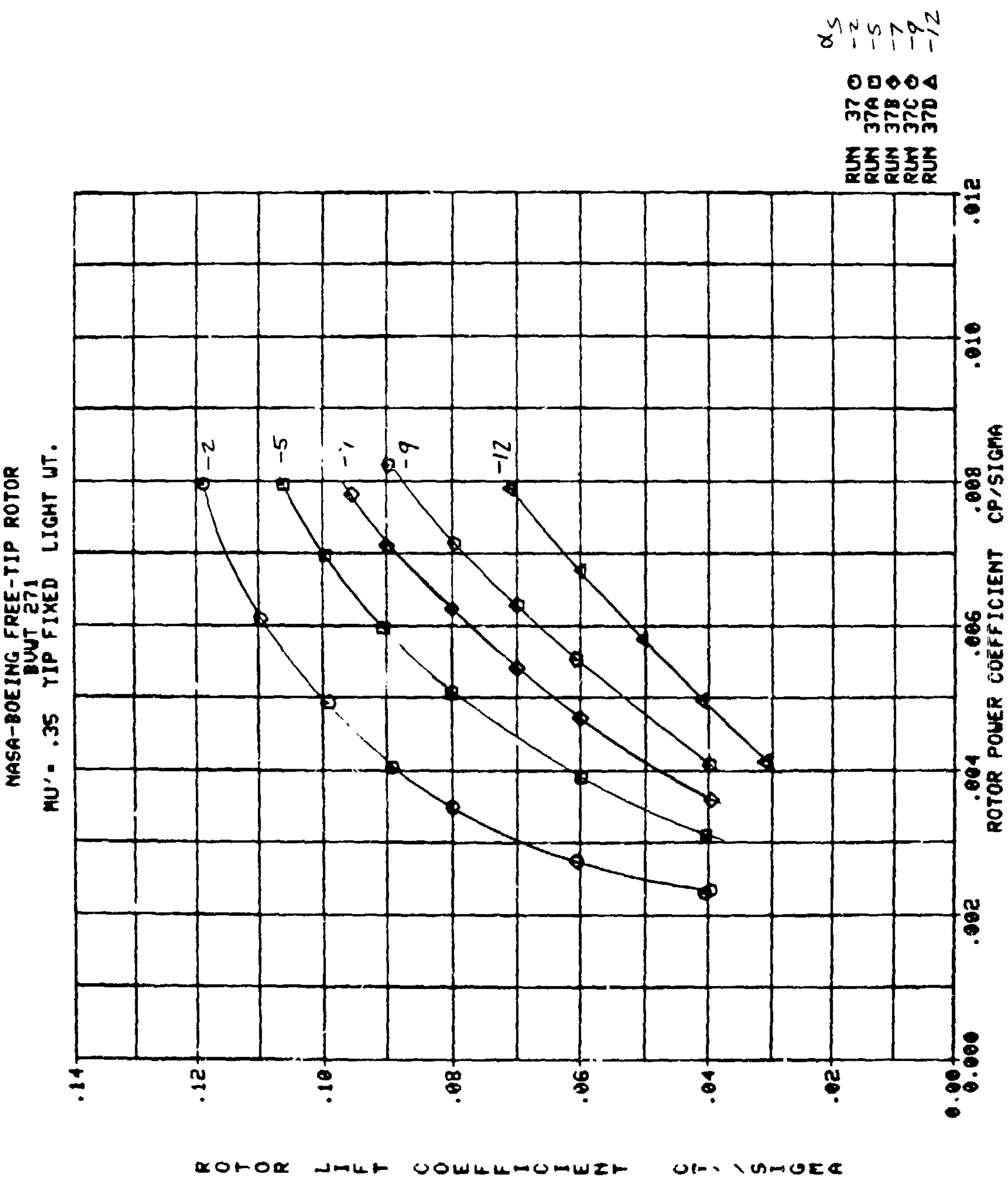
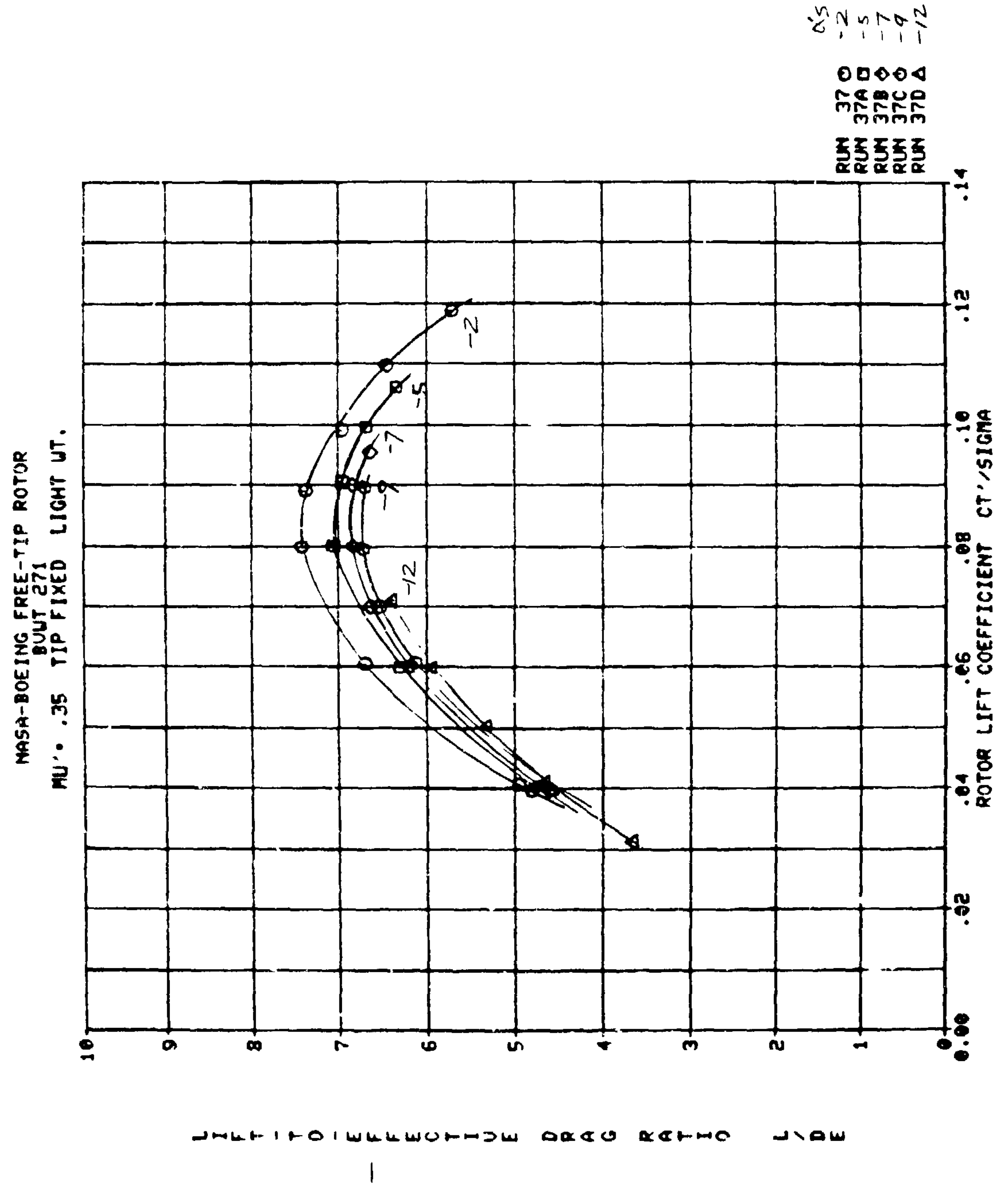
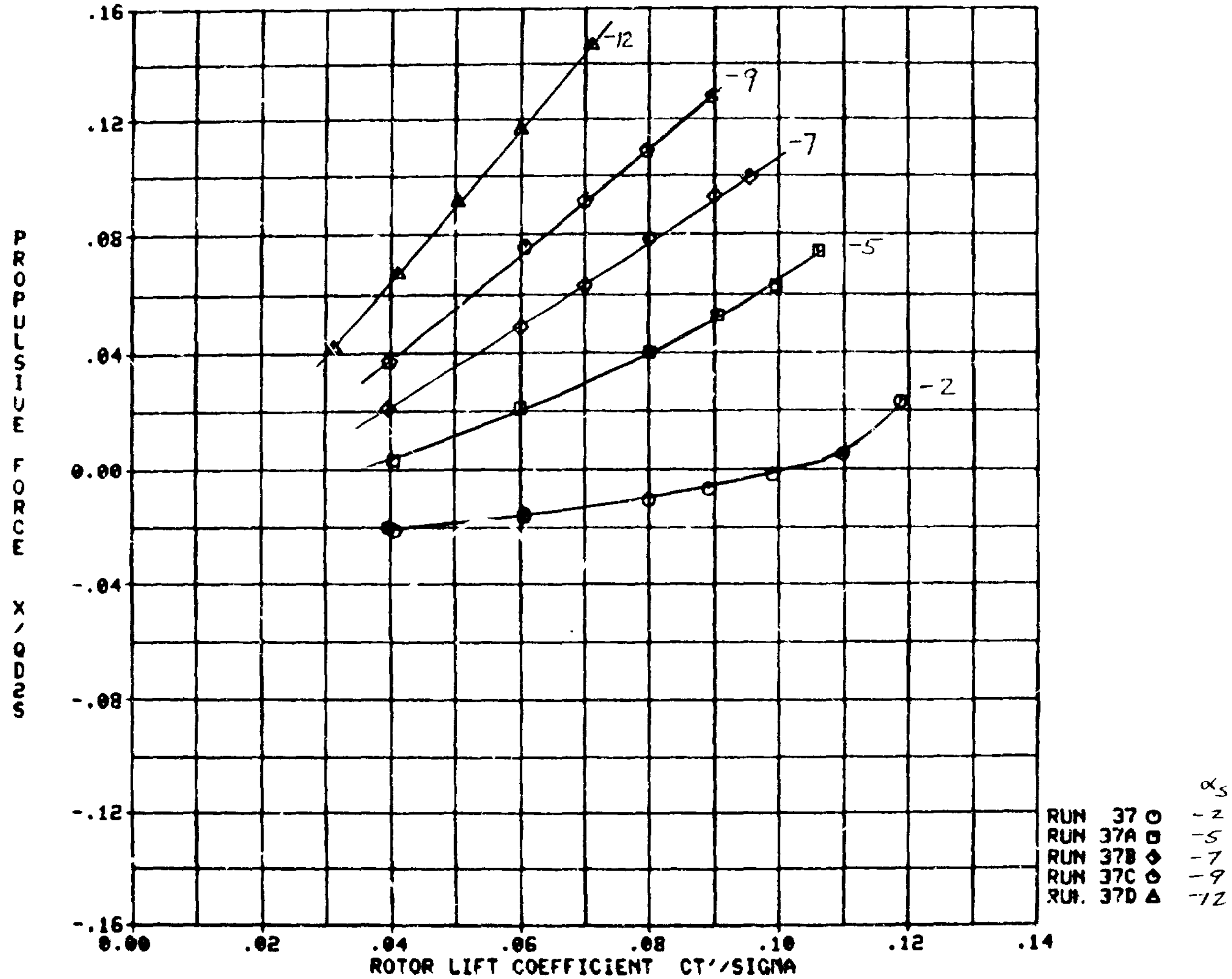



NASA-BOEING FREE-TIP ROTOR
BDWT 271
MU'= .30 TIP FIXED LIGHT WT.
RUN 38
RUN 38A
RUN 38B
RUN 38C
RUN 38D
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
50
100
150
200
250
300
350
400


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FIXED LIGHT WT.
RUN 37 -2
RUN 37A -5
RUN 37B -7
RUN 37C -9
RUN 37D -12
αs
ROTOR POWER COEFFICIENT CP/SIGMA
0.000
.002
.004
.006
.008
.010
.012
0.00
.02
.04
.06
.08
.10
.12
.14
-2
-5
-7
-9
-12


NASA-BOEING FREE-TIP ROTOR
BUUT 271
MU'= .35 TIP FIXED LIGHT WT.
RUN 37 ○ -2
RUN 37A □ -5
RUN 37B ◇ -7
RUN 37C ⌀ -9
RUN 37D △ -12
ROTOR LIFT COEFFICIENT CT'/SIGMA
DRAG RATIO L/DE

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FIXED LIGHT WT.



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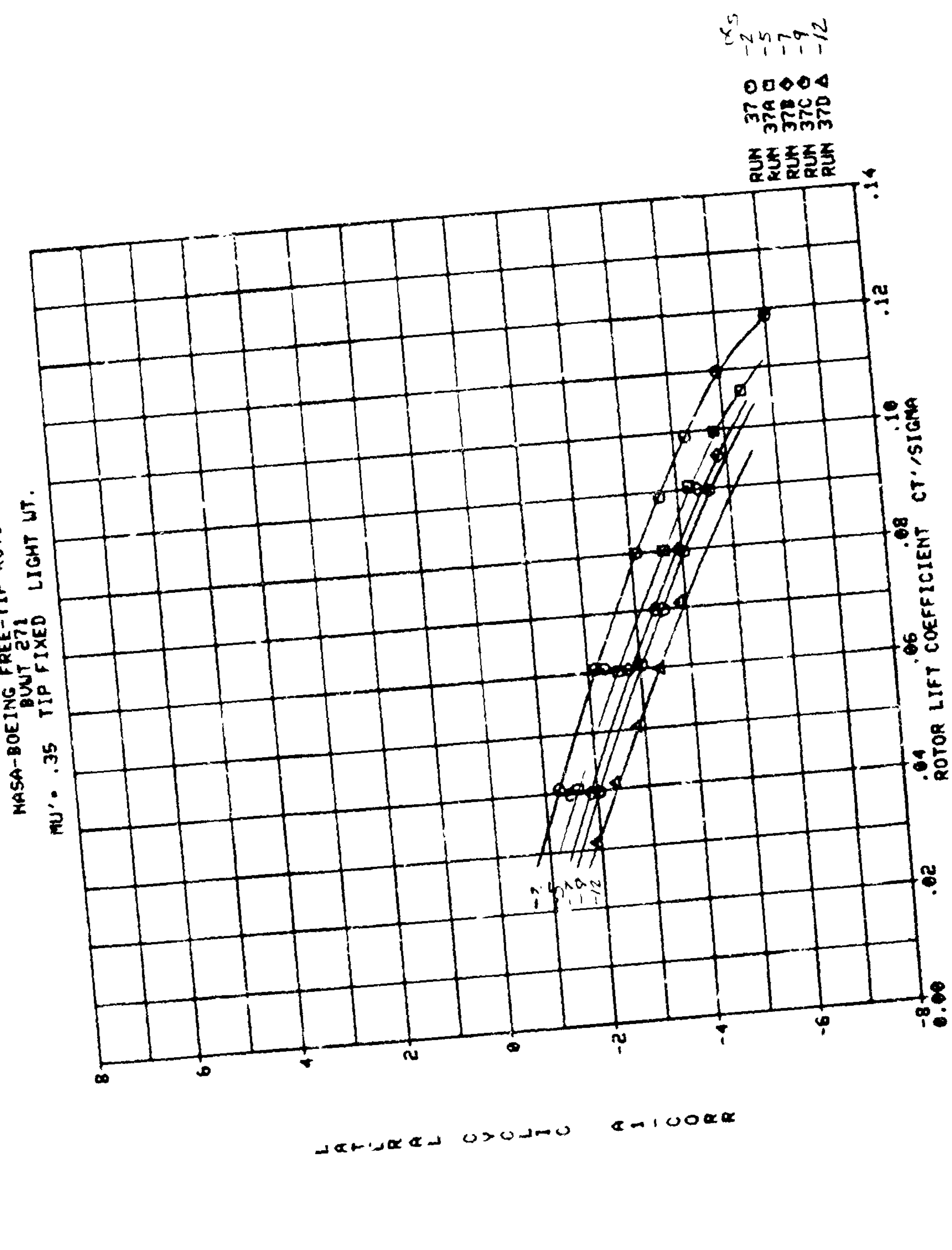
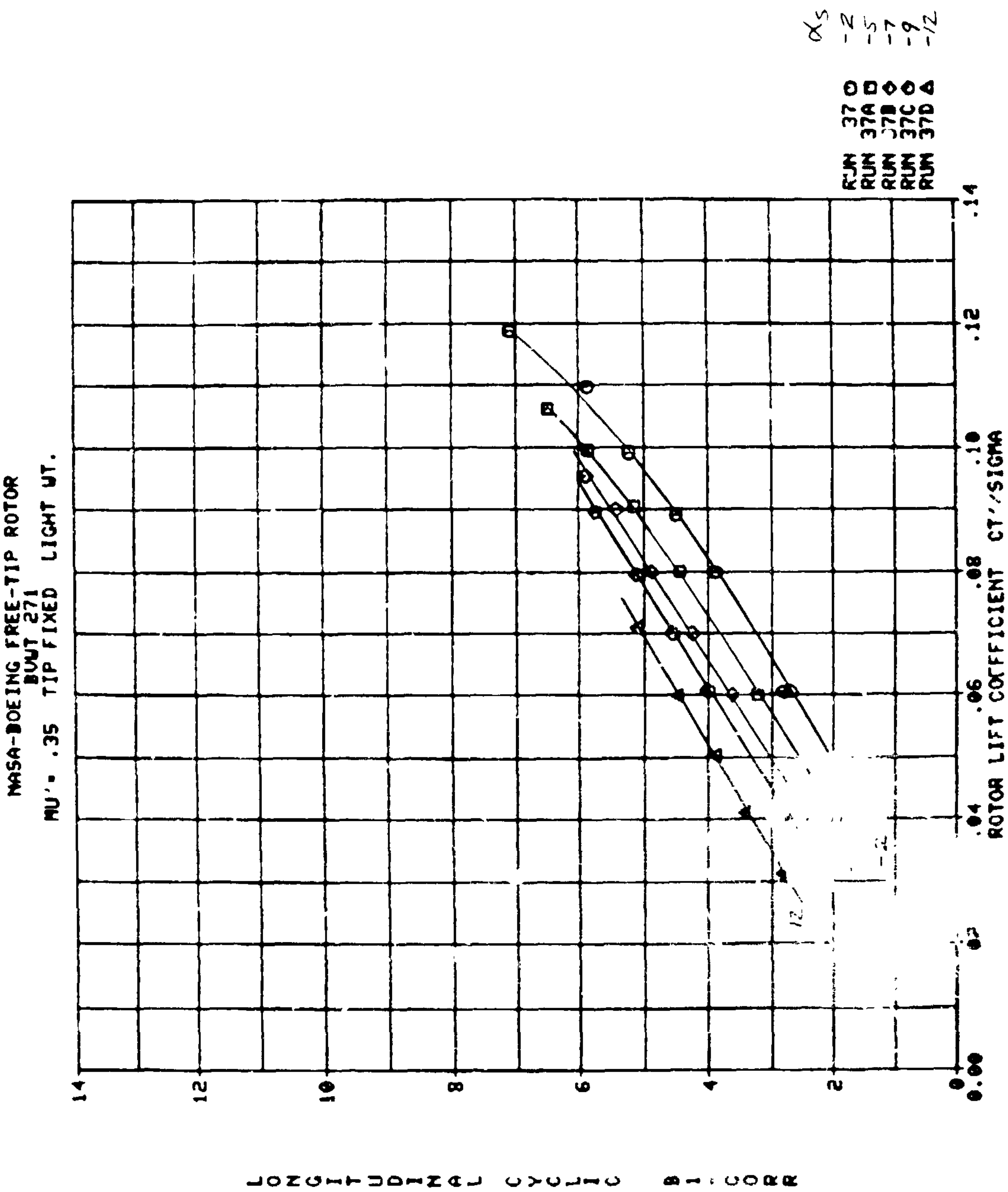
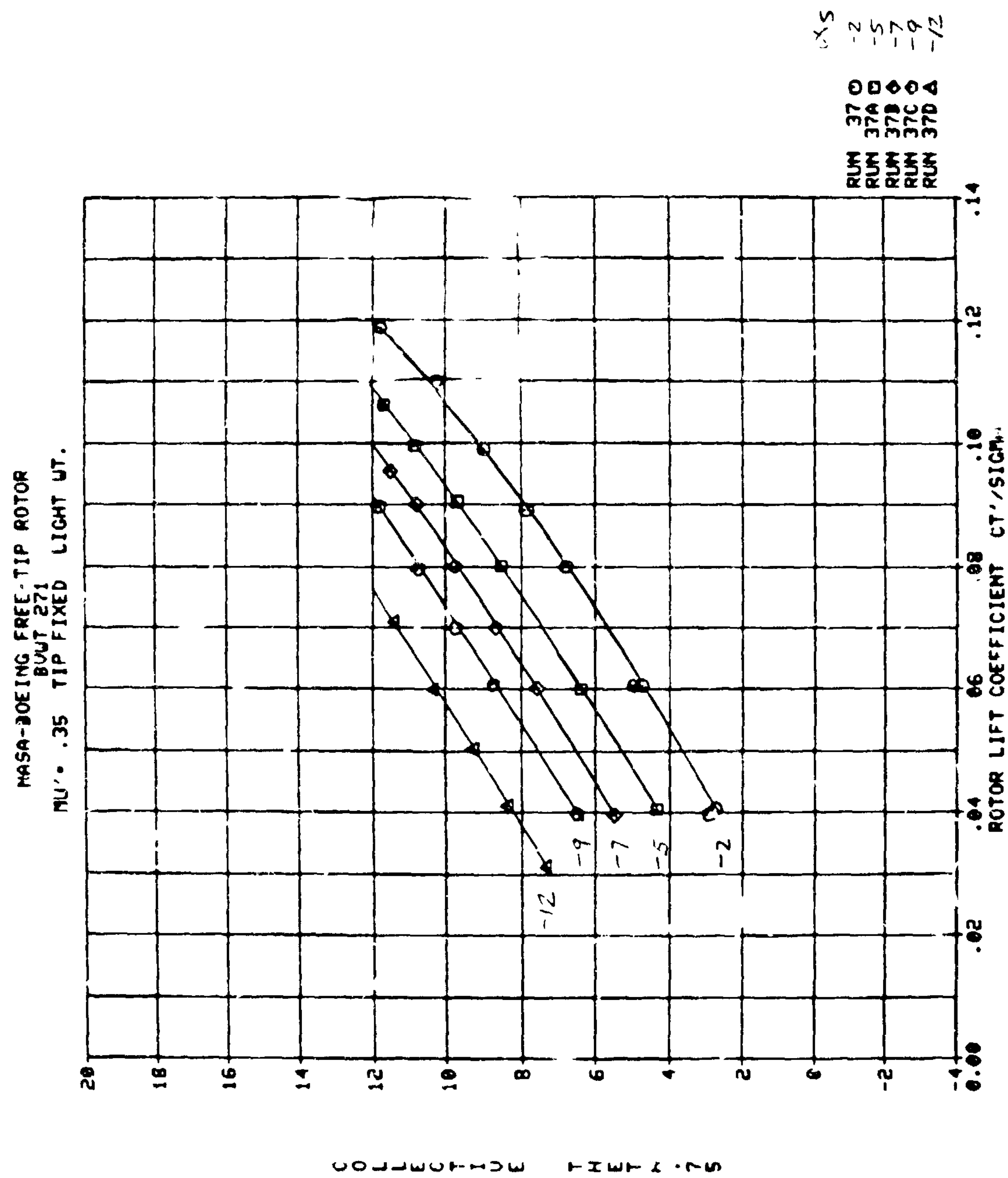
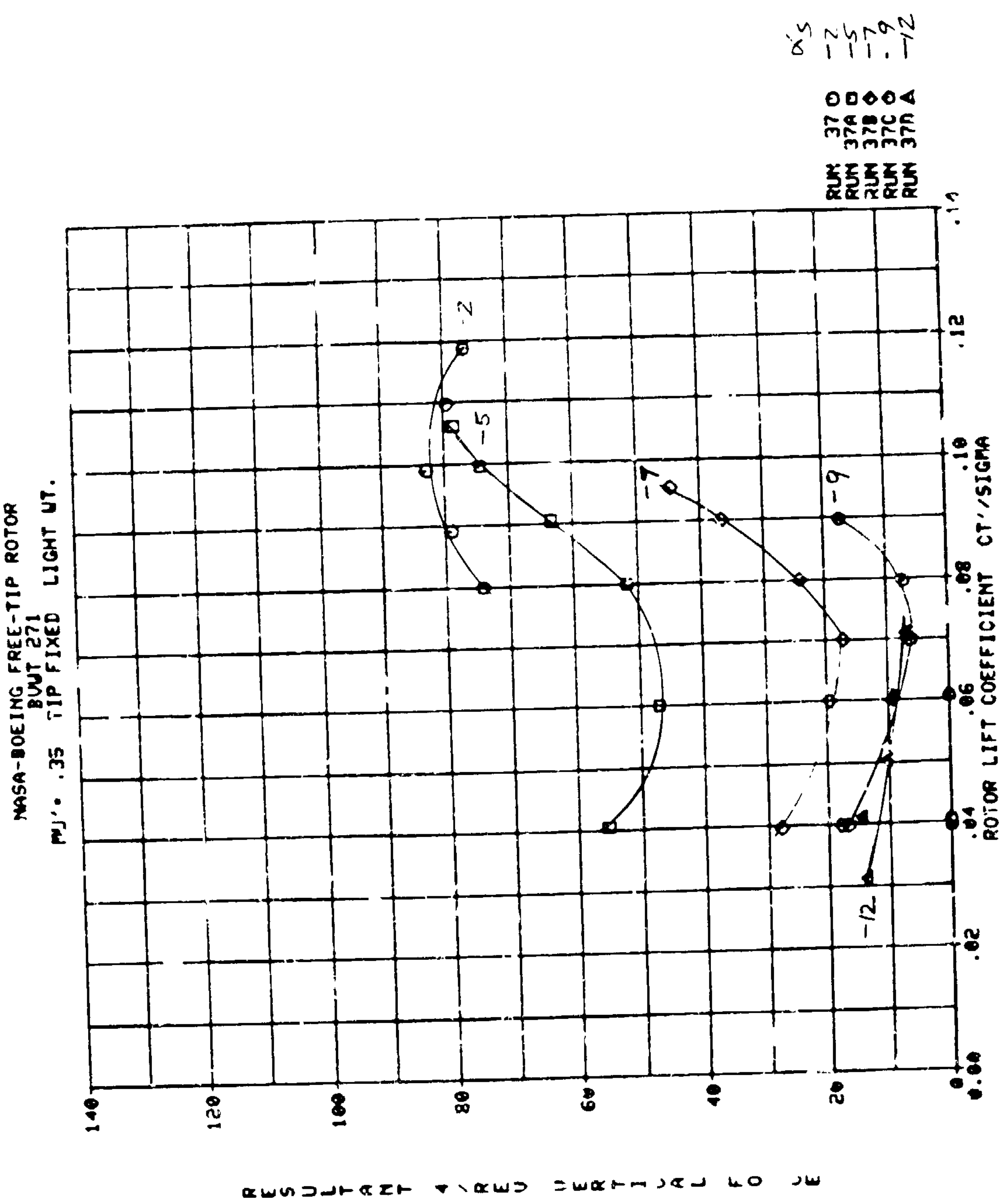



NASA-BOEING FREE-TIP ROTOR
BWWT 271
MU'= .35 TIP FIXED LIGHT WT.
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.04
.06
.08
.10
.12
.14
0
2
4
6
8
10
12
14
RUN 37
RUN 37A
RUN 37B
RUN 37C
RUN 37D
αs
-2
-5
-7
-9
-12


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FIXED LIGHT WT.
RUN 37
RUN 37A
RUN 37B
RUN 37C
RUN 37D
ROTOR LIFT COEFFICIENT CT'/SIGMA
-2
-5
-7
-9
-12


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FIXED LIGHT WT.
RUN 37 O -2
RUN 37A □ -5
RUN 37B ◇ -7
RUN 37C ○ -9
RUN 37D △ -12
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
20
40
60
80
100
120
140

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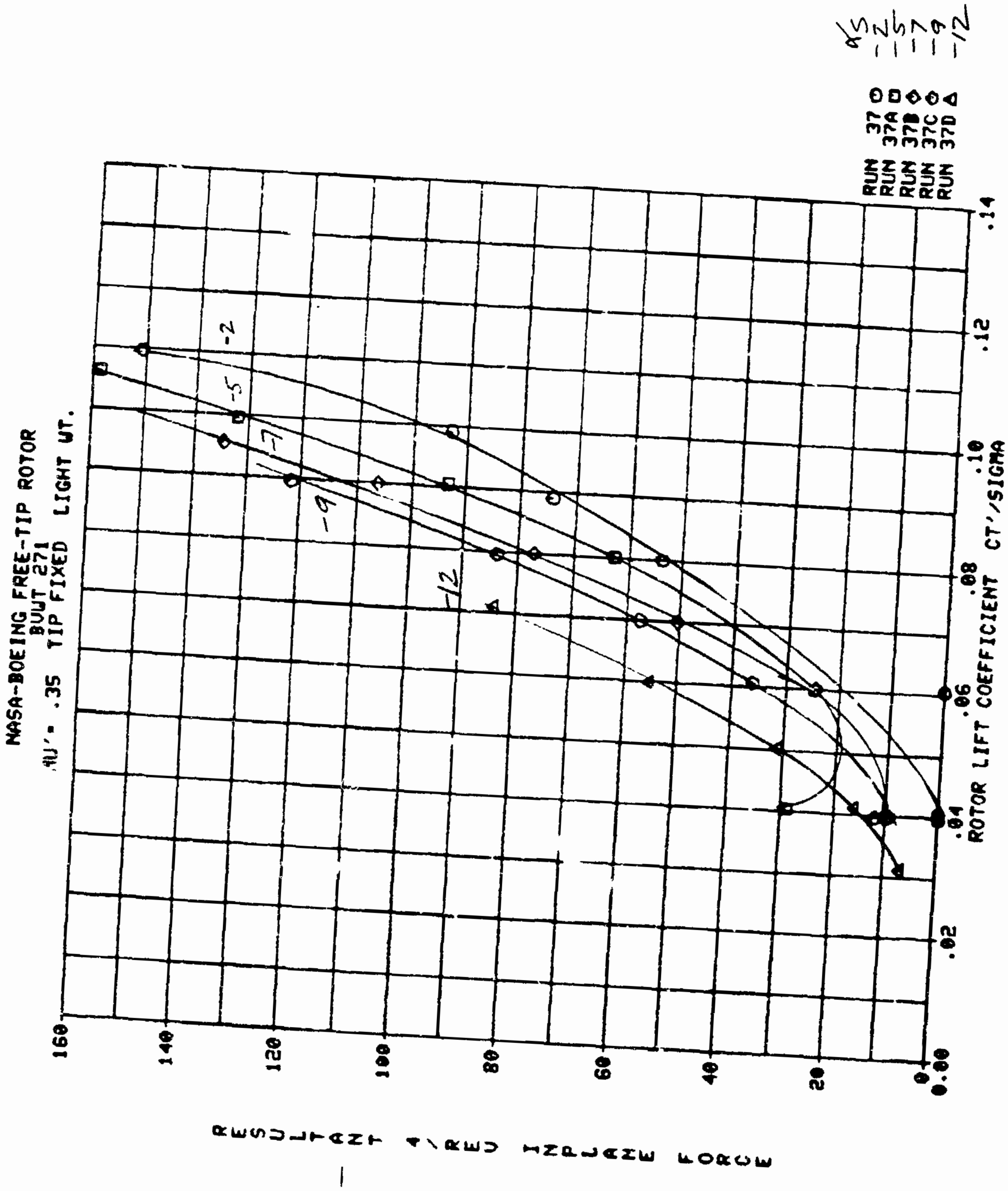
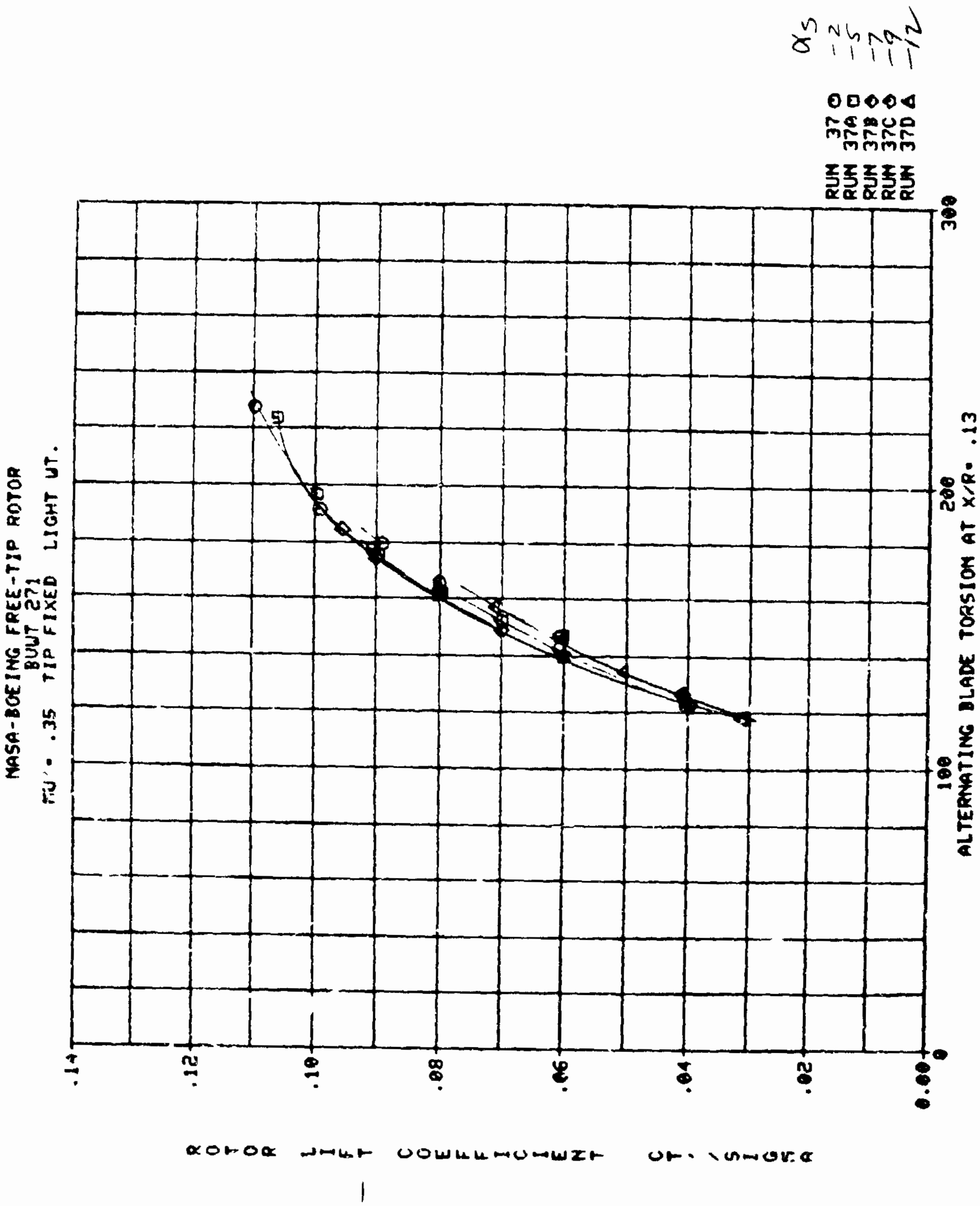
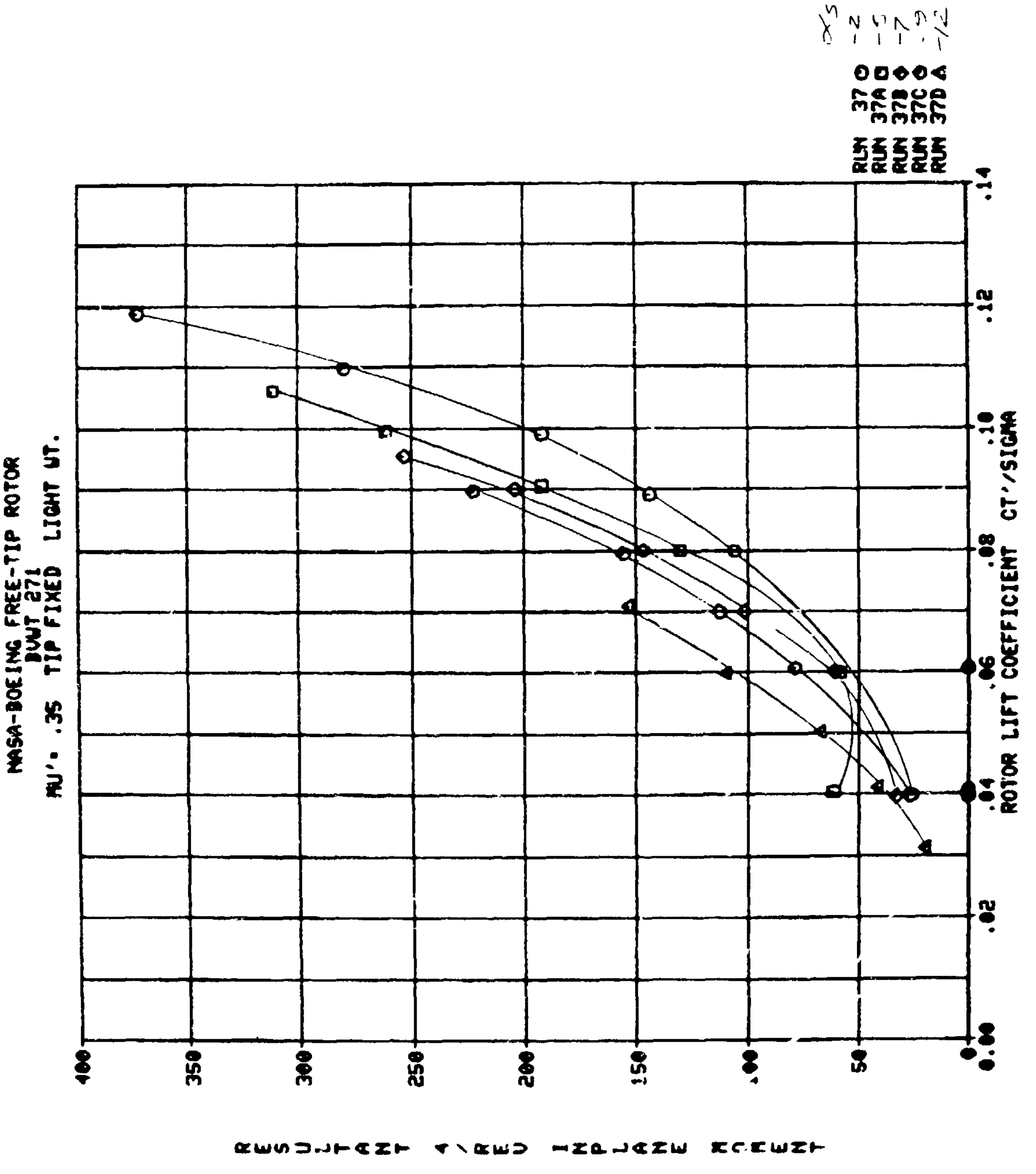
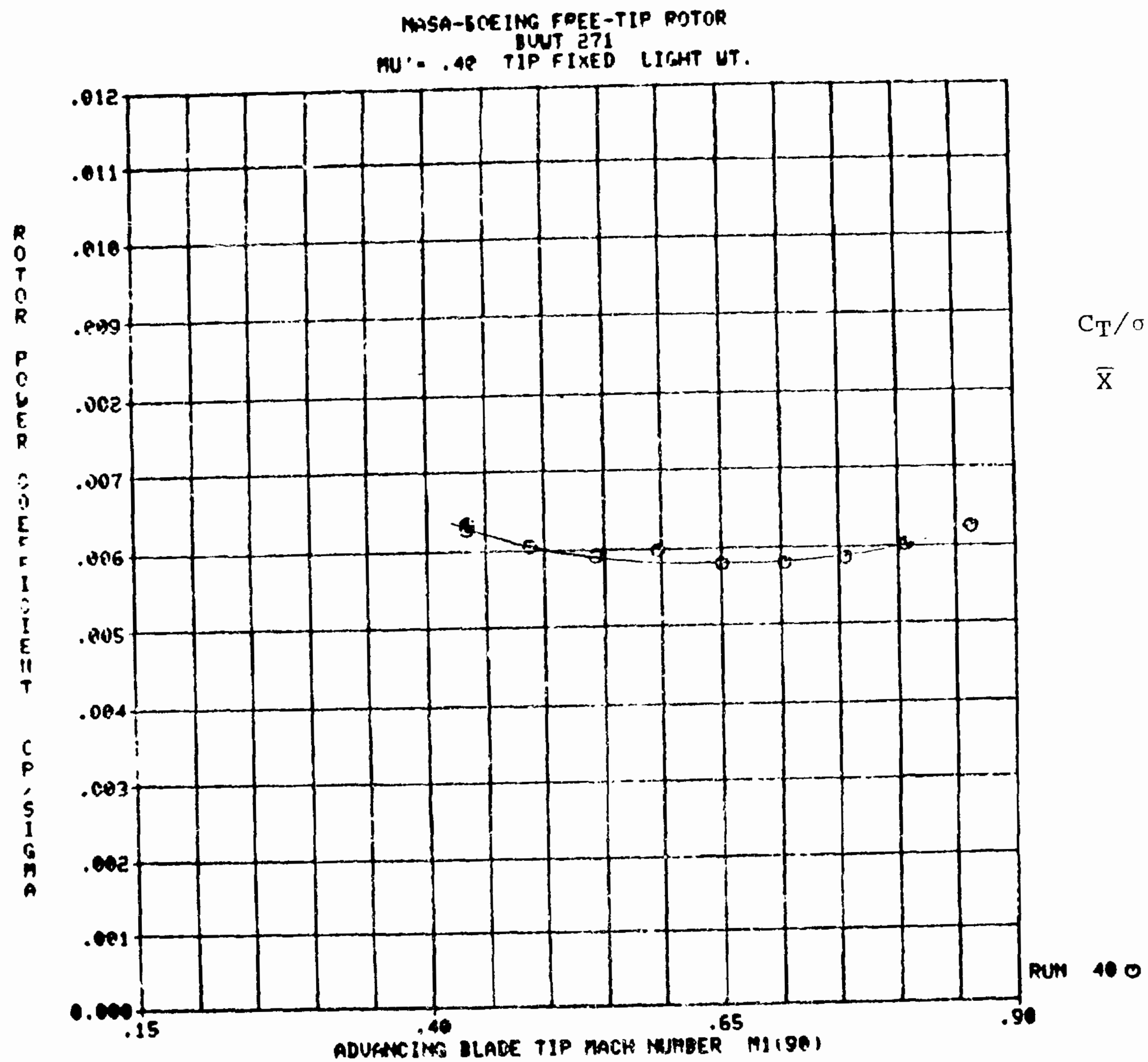



NASA-BOEING FREE-TIP ROTOR
BUWT 271
MU = .35 TIP FIXED LIGHT WT.
RUN 37 O
RUN 37A □
RUN 37B ◇
RUN 37C ◇
RUN 37D △
αs
-2
-5
-7
-9
-12
ALTERNATING BLADE TORSION AT X/R = .13
0
100
200
300
0.00
.02
.04
.06
.08
.10
.12
.14


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FIXED LIGHT WT.
RUN 37
RUN 37A
RUN 37B
RUN 37C
RUN 37D
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
50
100
150
200
250
300
350
400



C_T/σ = .07

$\overline{X}$ = .05

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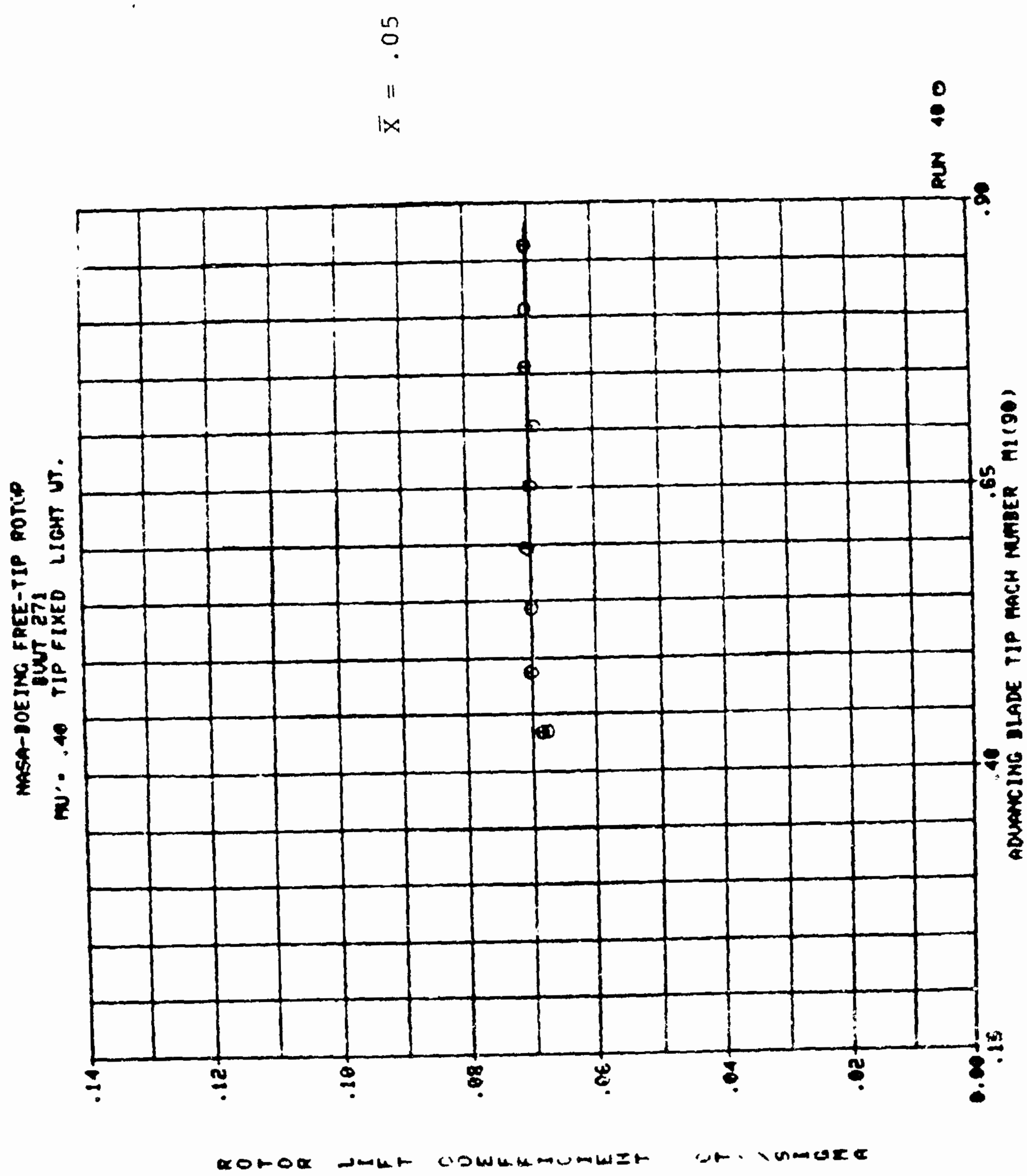

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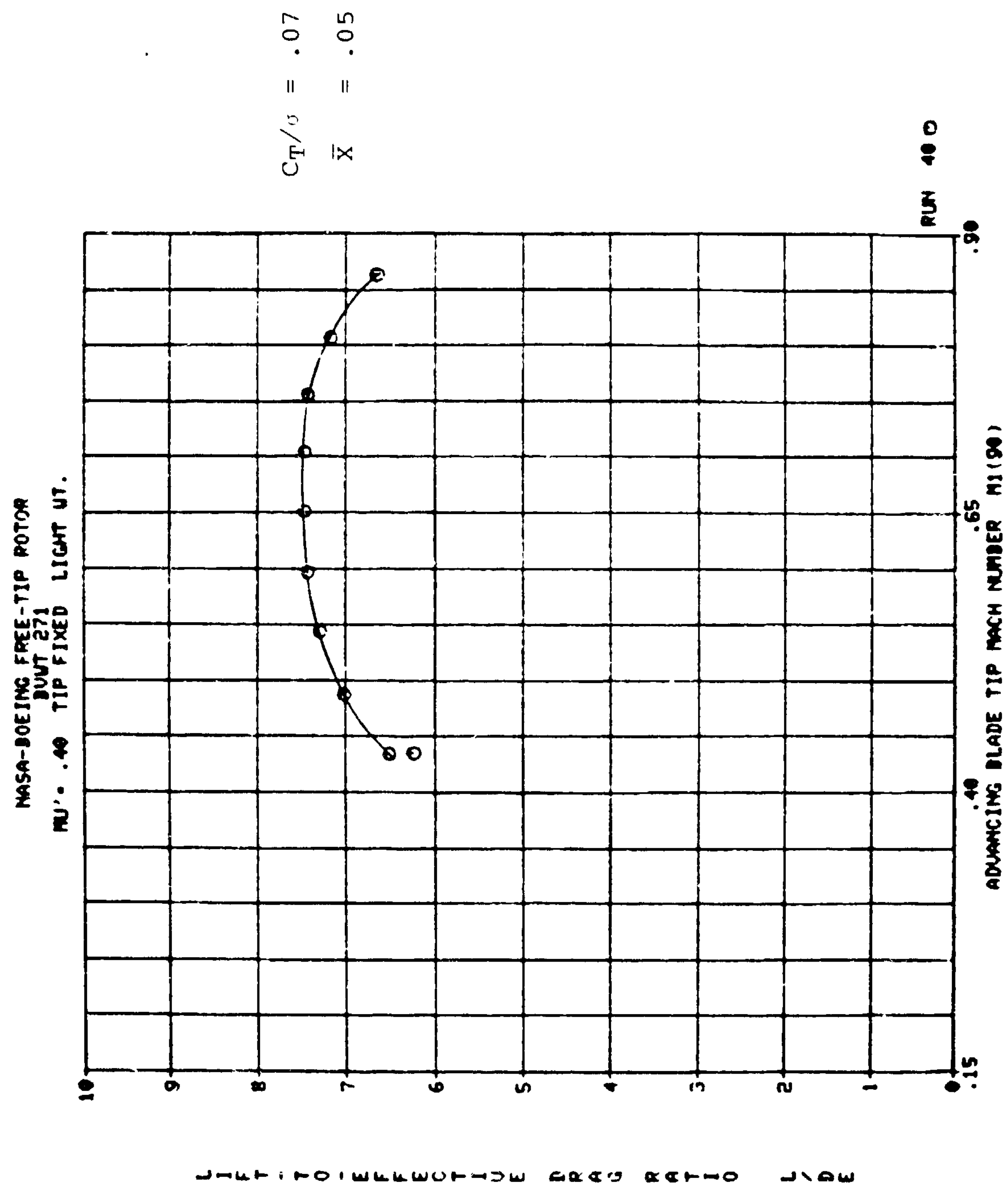

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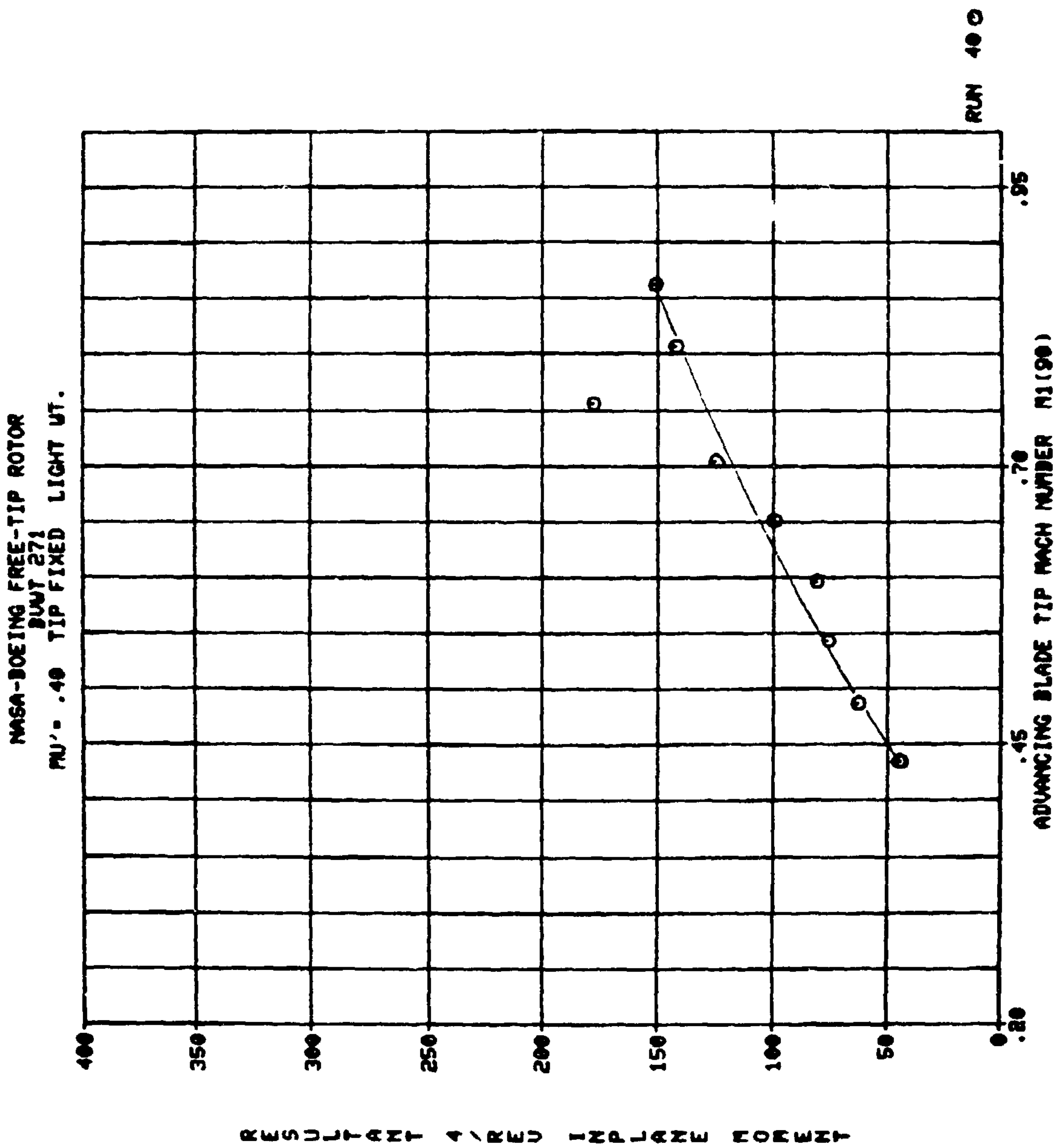

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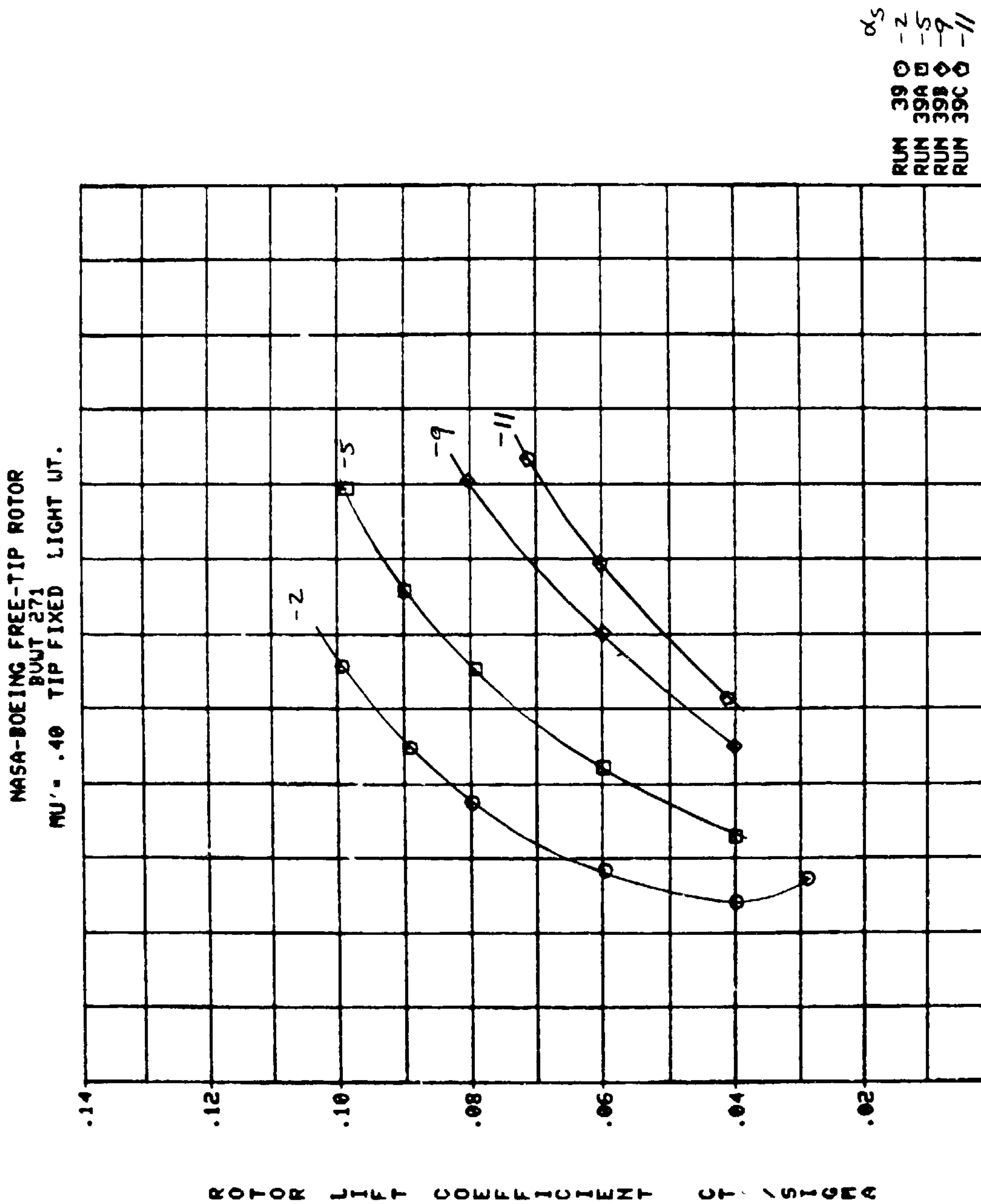

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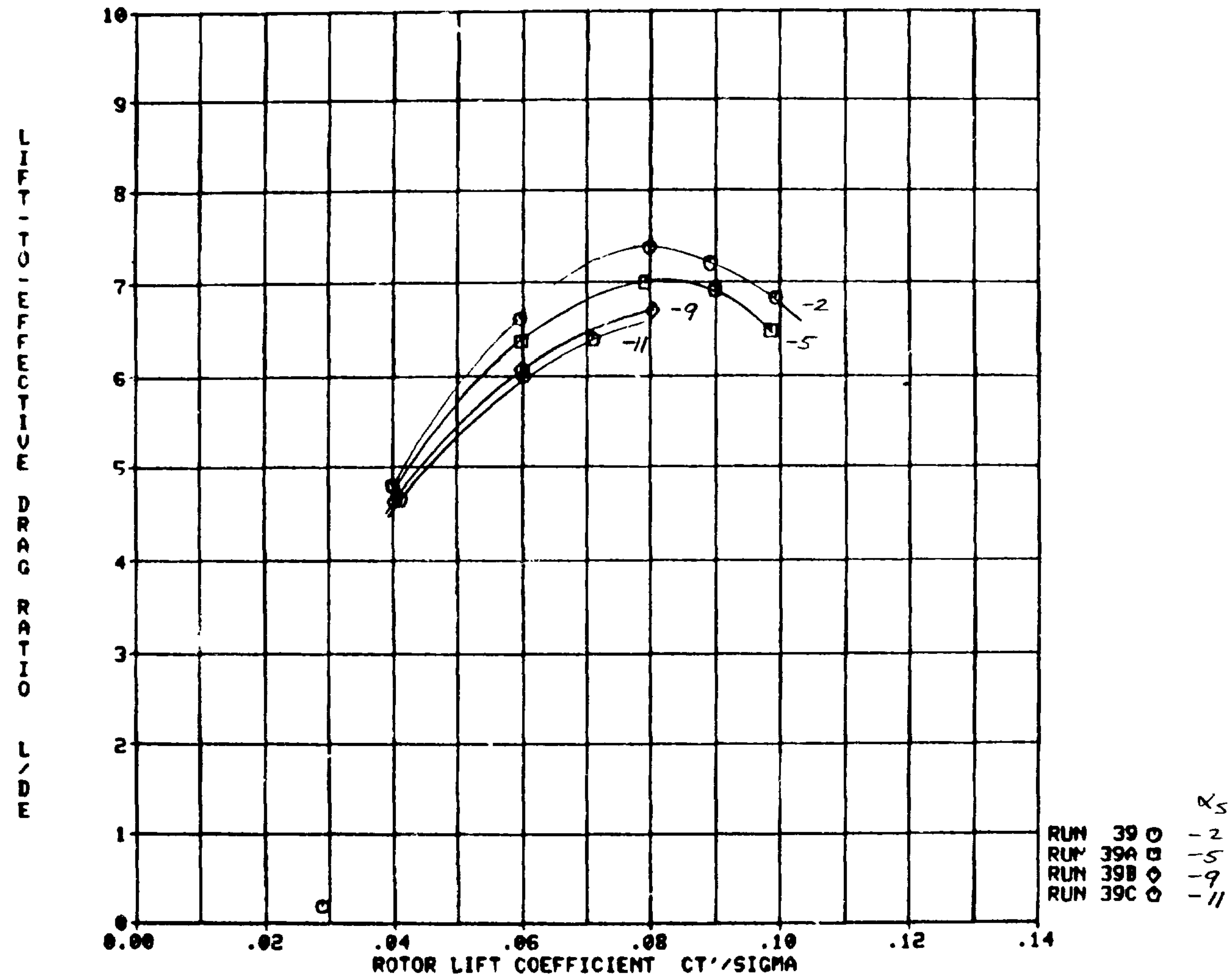
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .40 TIP FIXED LIGHT WT.



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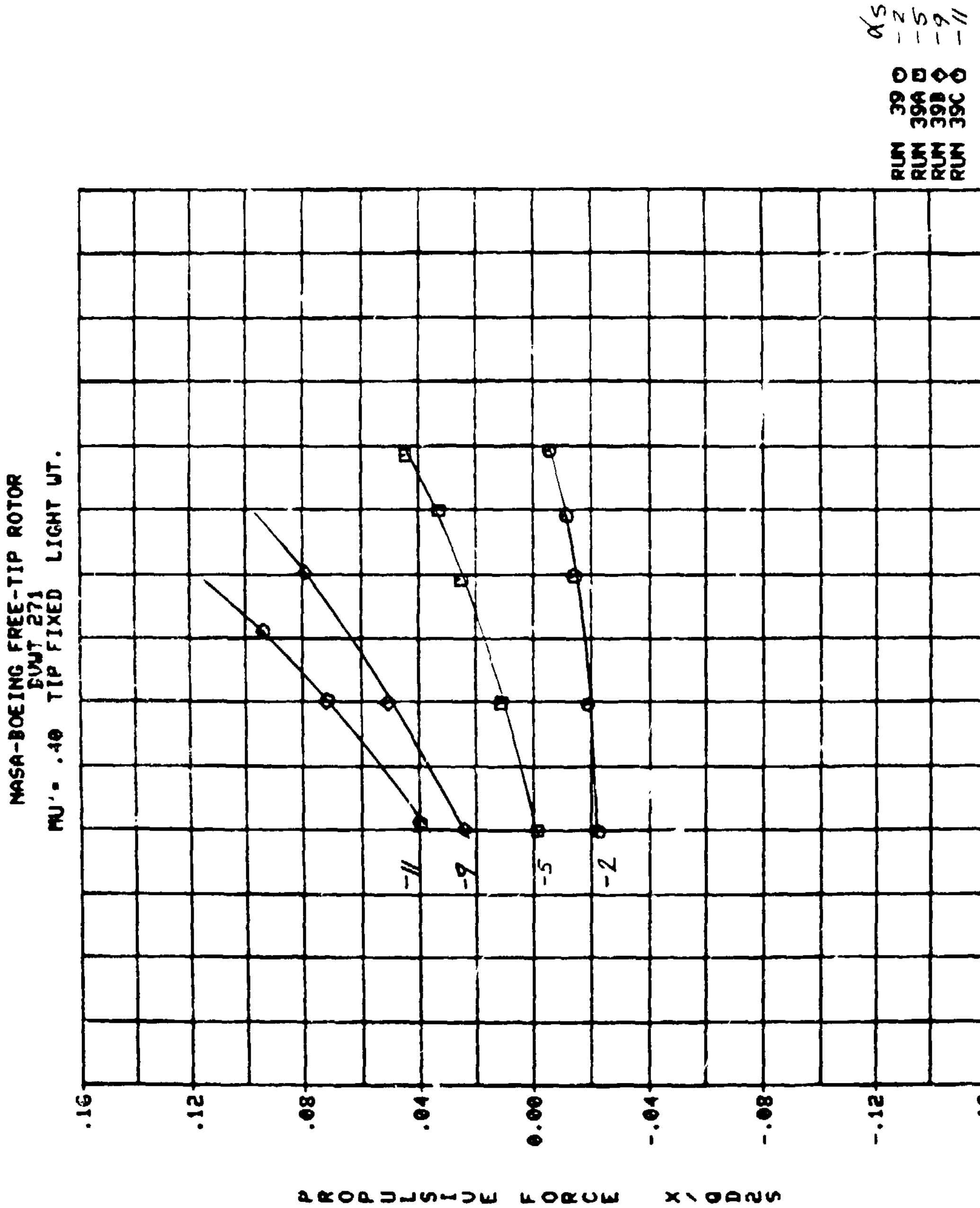

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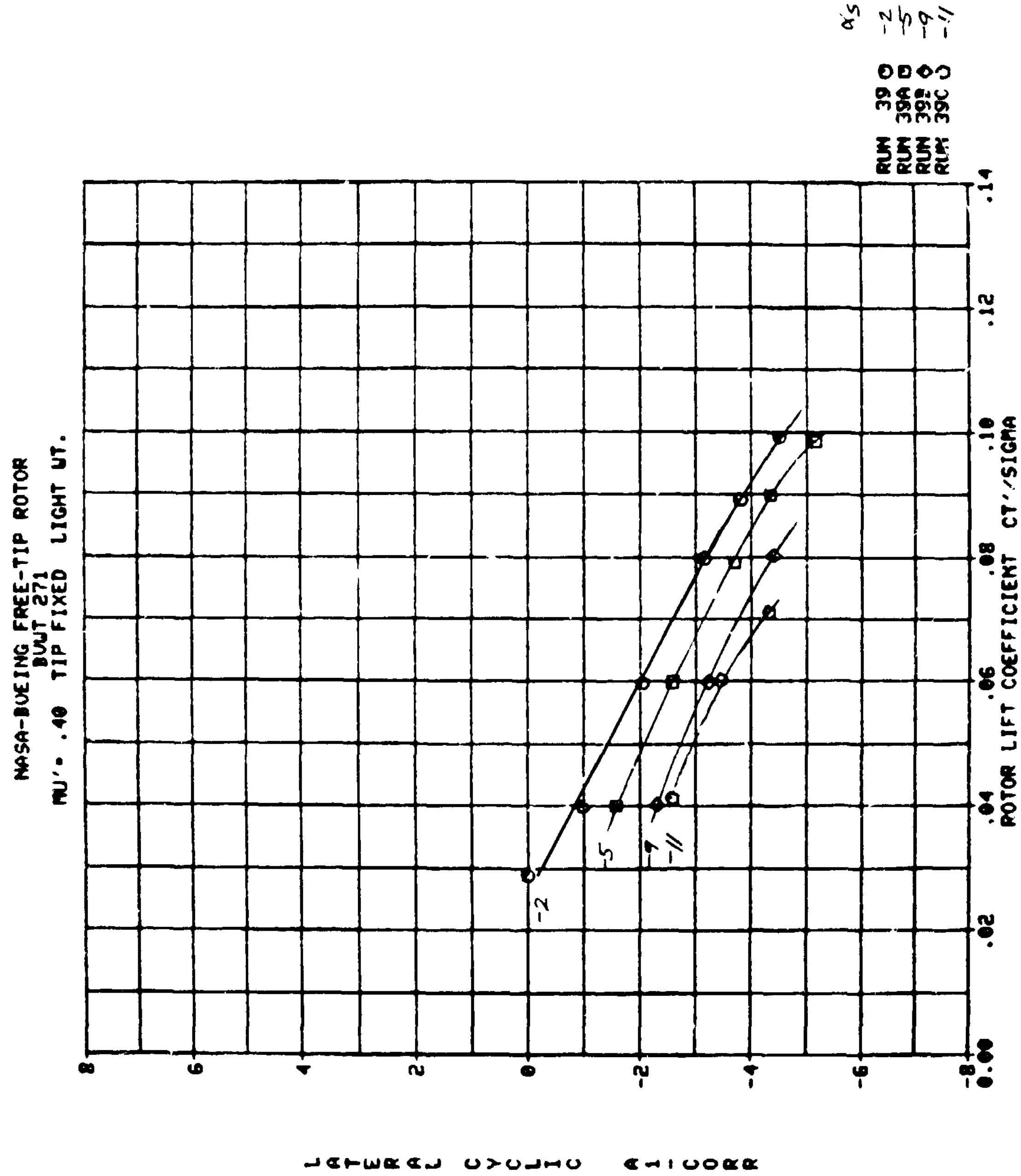

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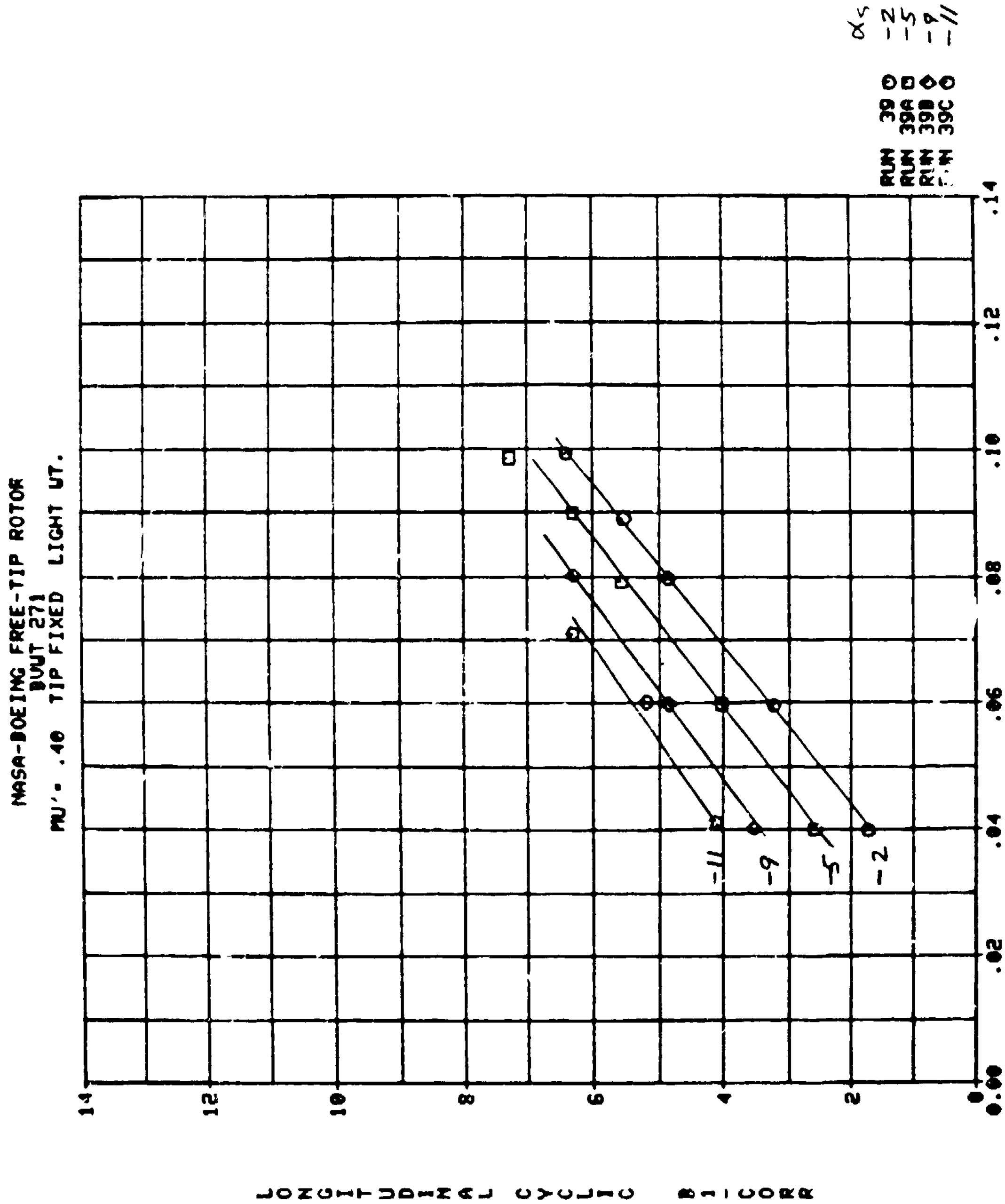
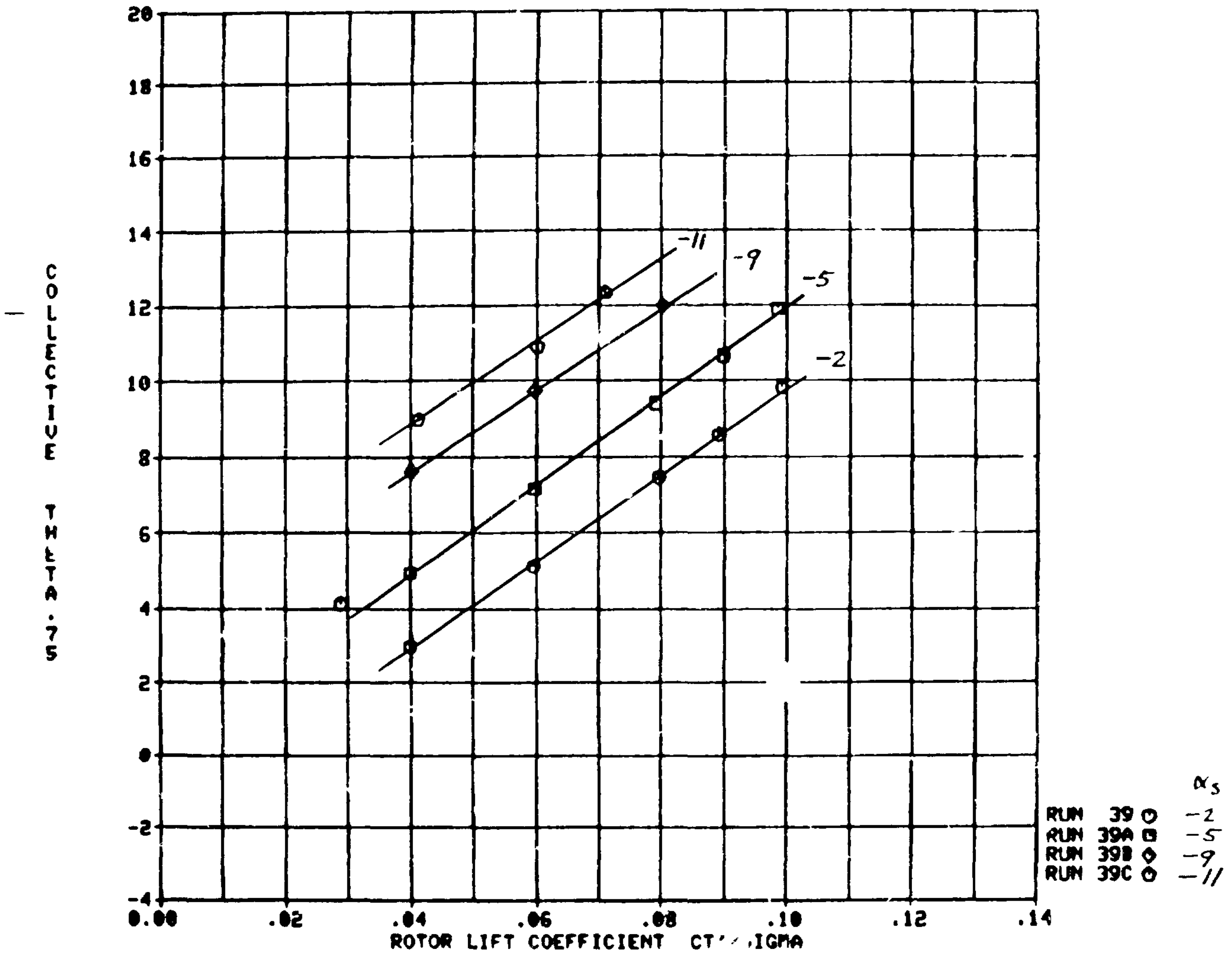
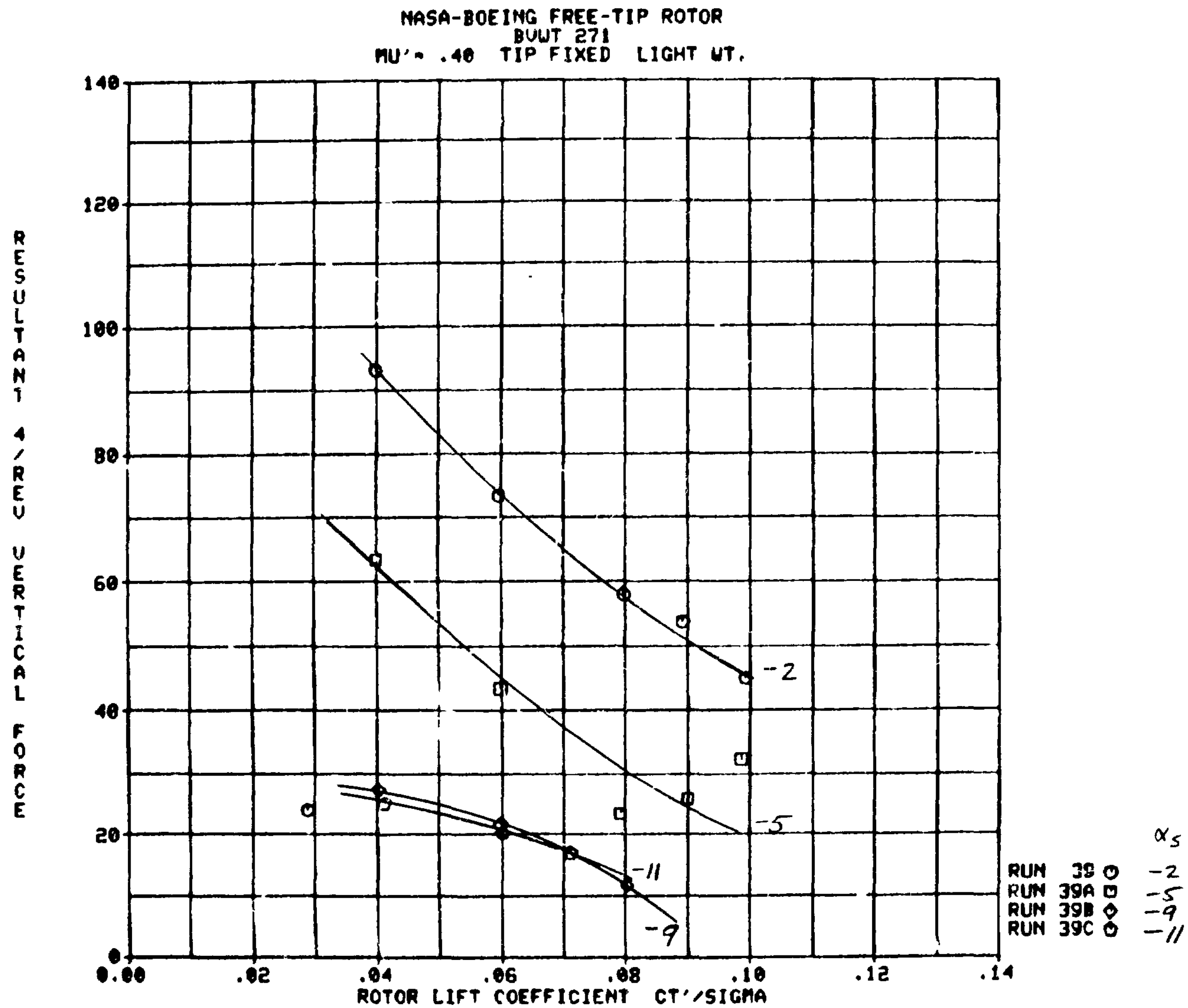


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .40 TIP FIXED LIGHT WT.




NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .40 TIP FIXED LIGHT WT.
RESULTANT 4/REV VERTICAL FORCE
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
20
40
60
80
100
120
140
α_s
RUN 39 -2
RUN 39A -5
RUN 39B -9
RUN 39C -11
-2
-5
-11
-9

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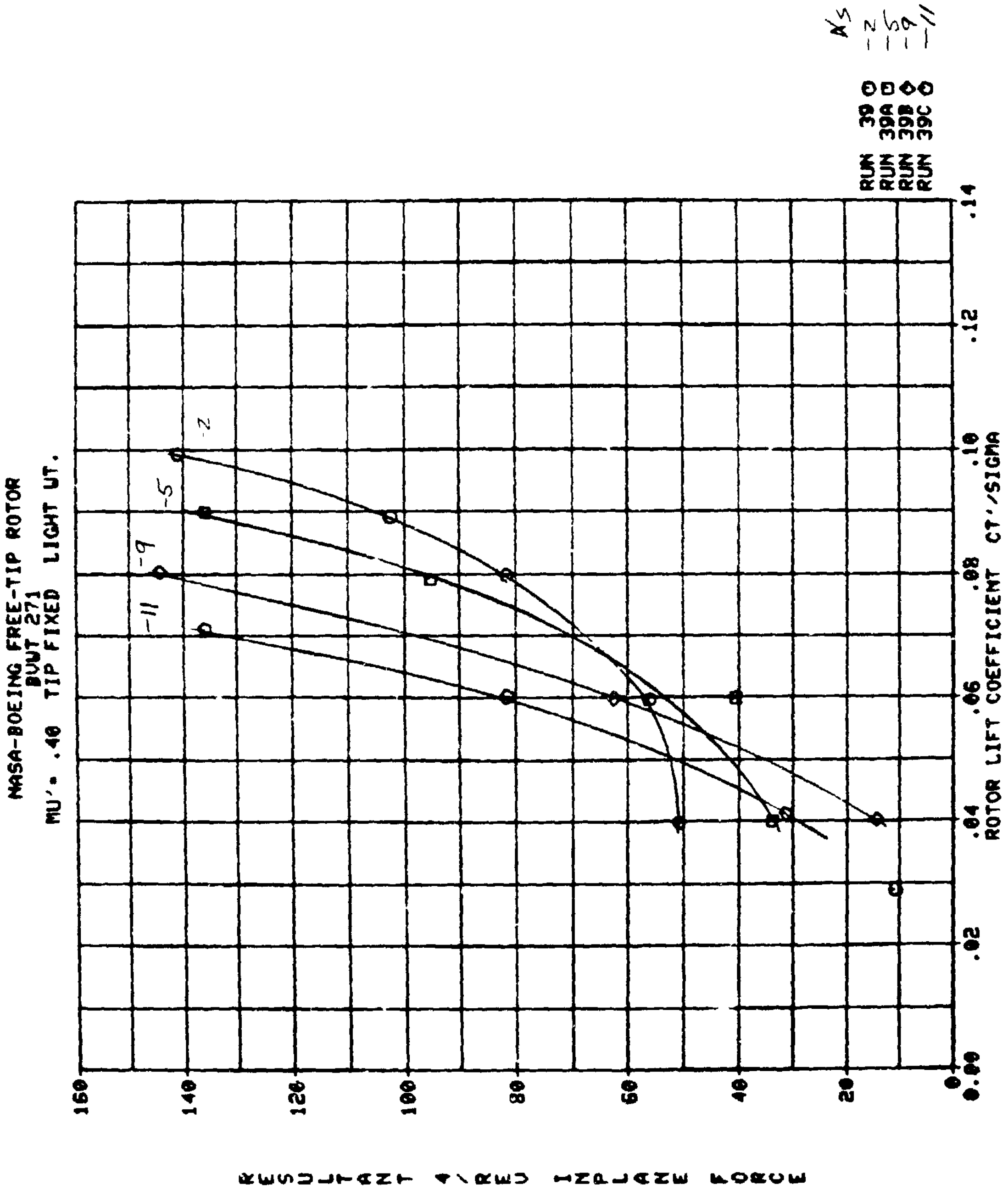

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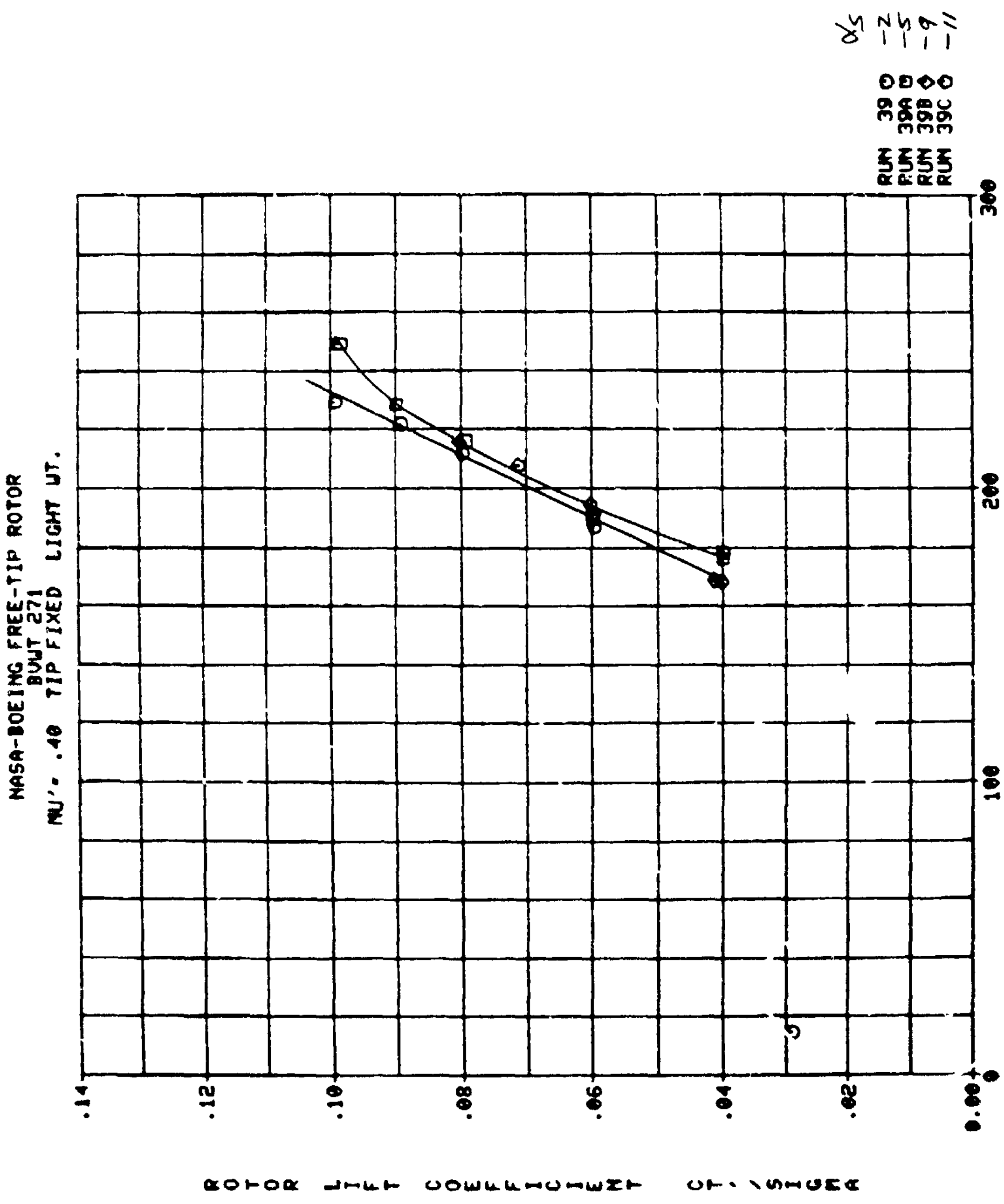

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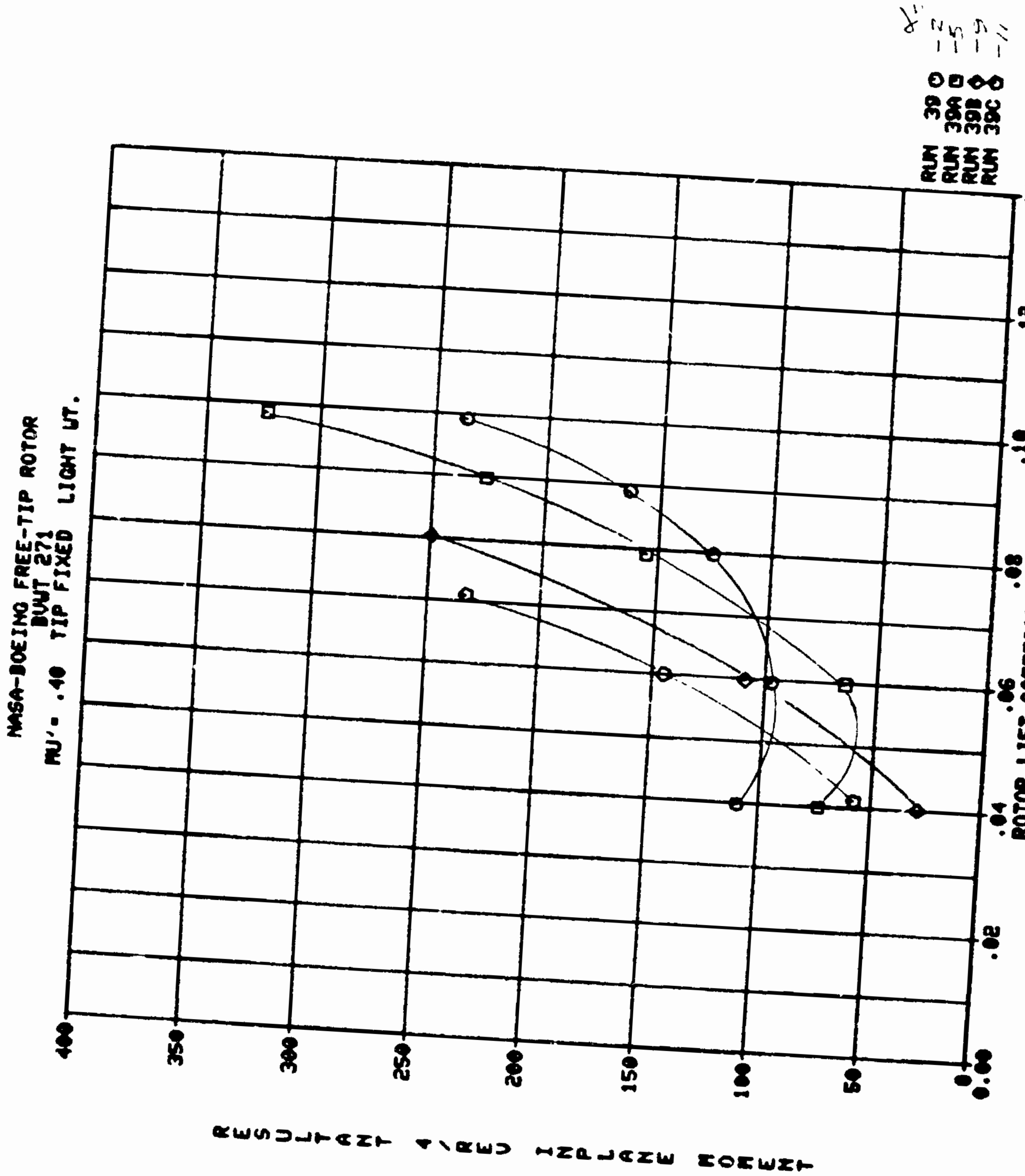

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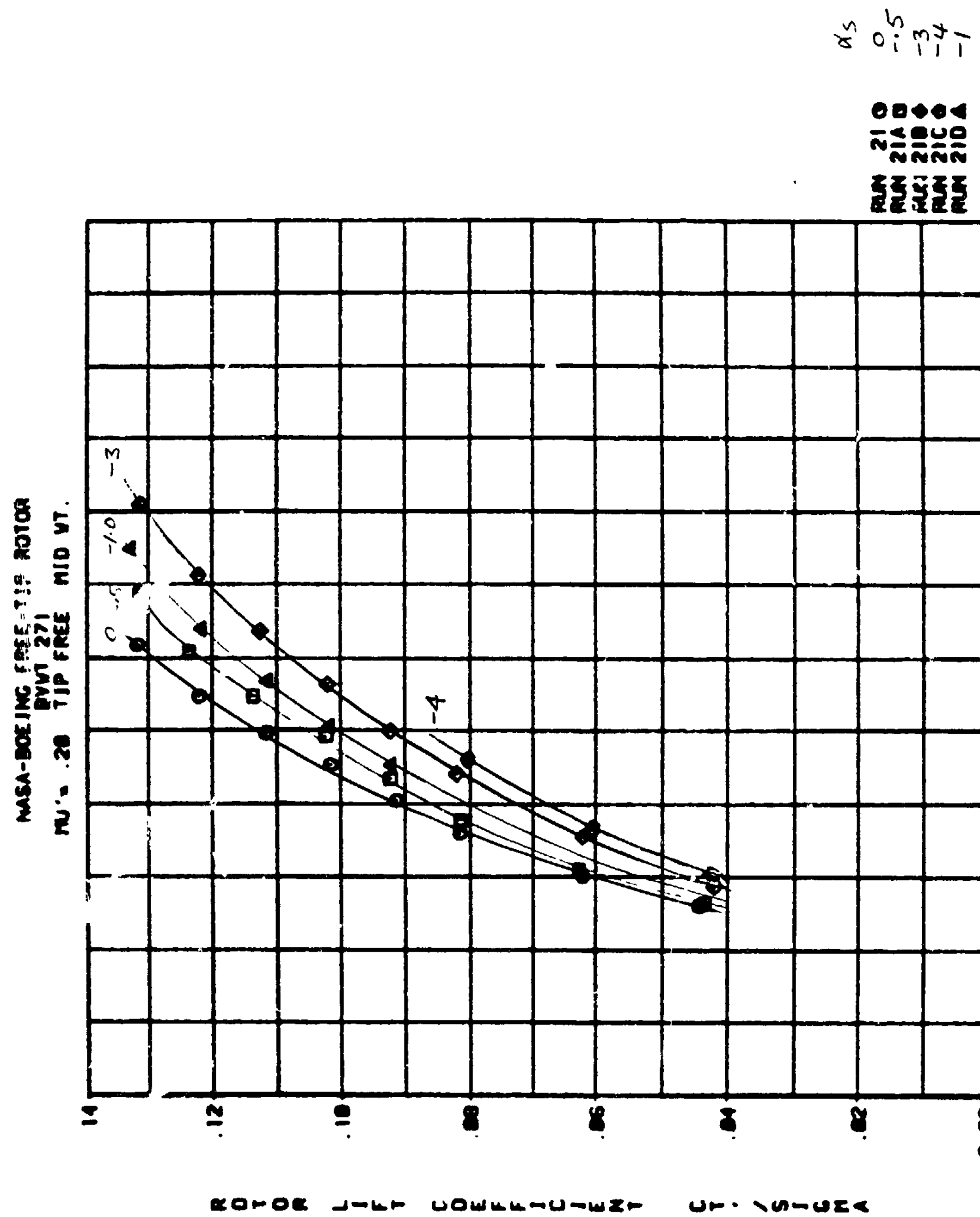

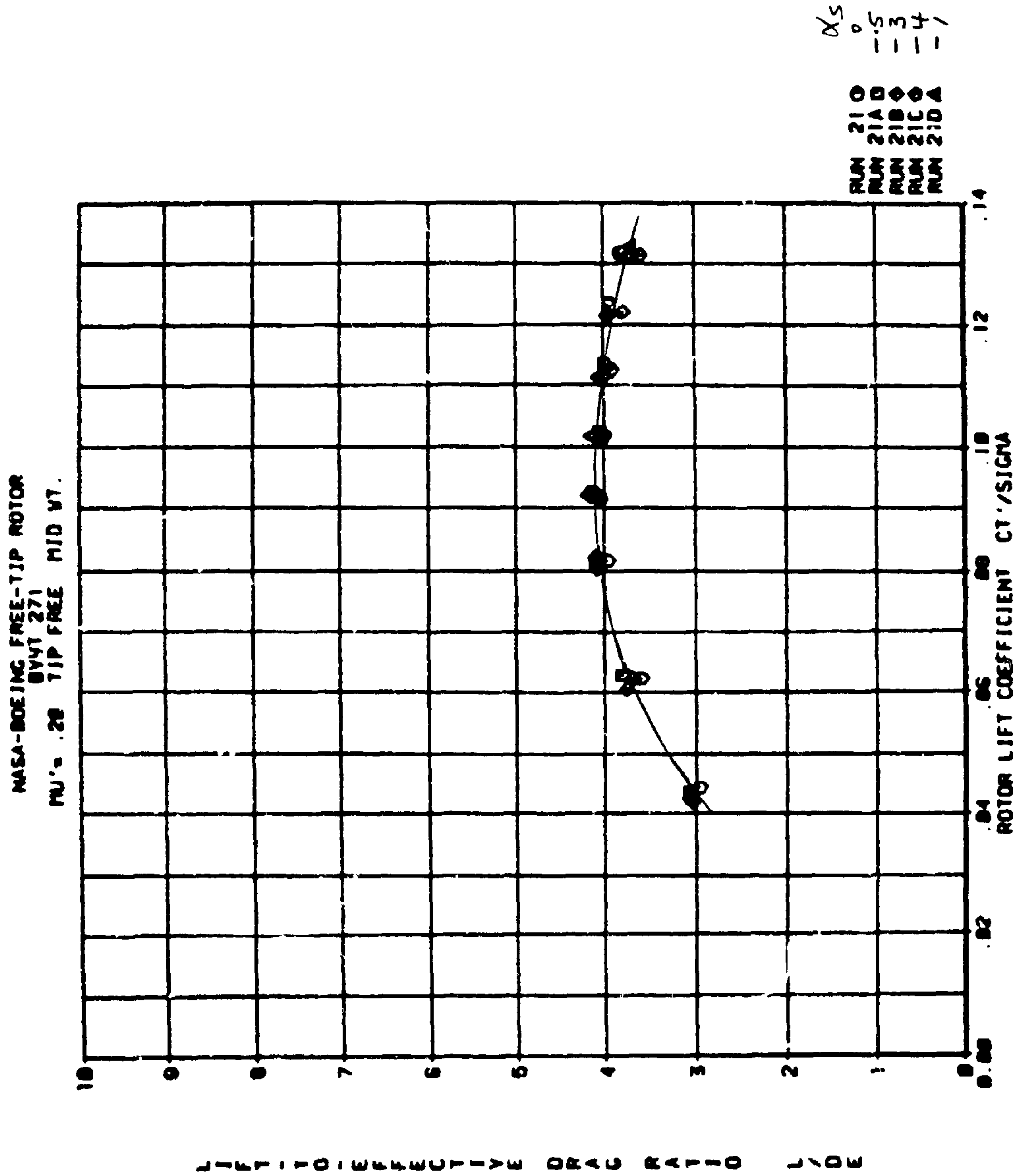
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .20 TIP FREE MID WT.
RUN 21 ○
RUN 21A □
RUN 21B ◆
RUN 21C ●
RUN 21D ▲
ROTOR LIFT COEFFICIENT CT'/SIGMA
DRAG RATIO
0.00
.02
.04
.06
.08
.10
.12
.14
0
1
2
3
4
5
6
7
8
9
10

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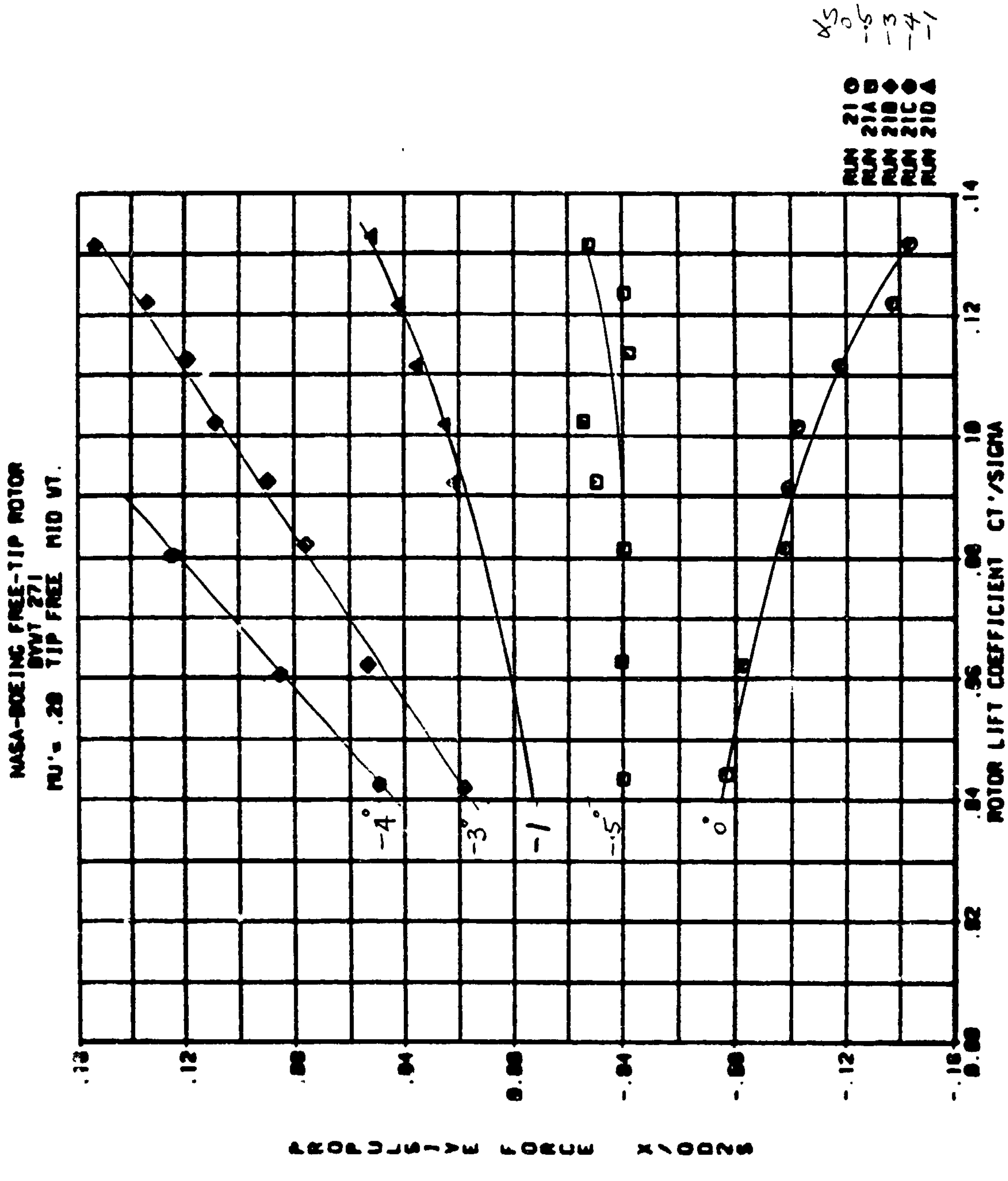

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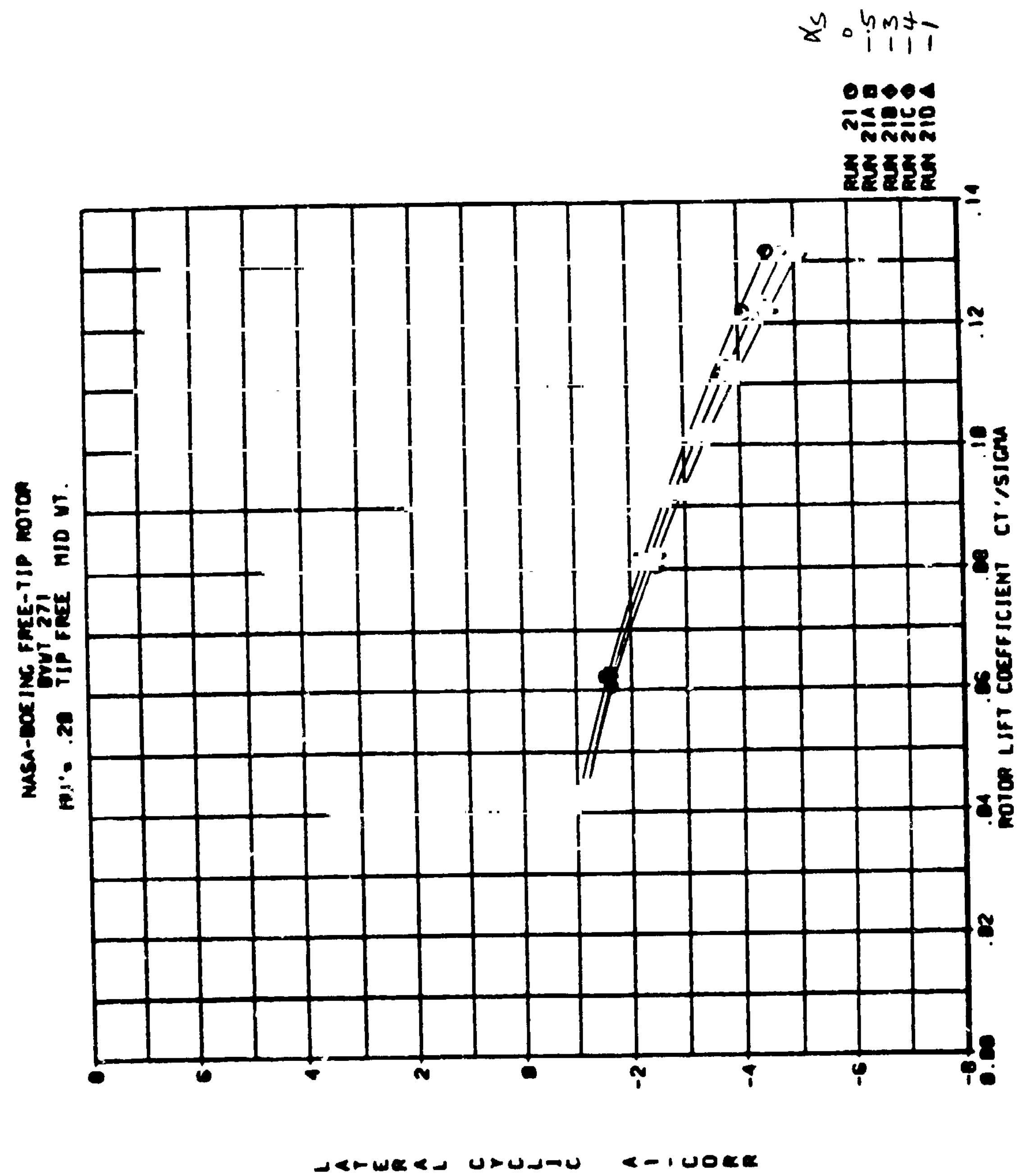
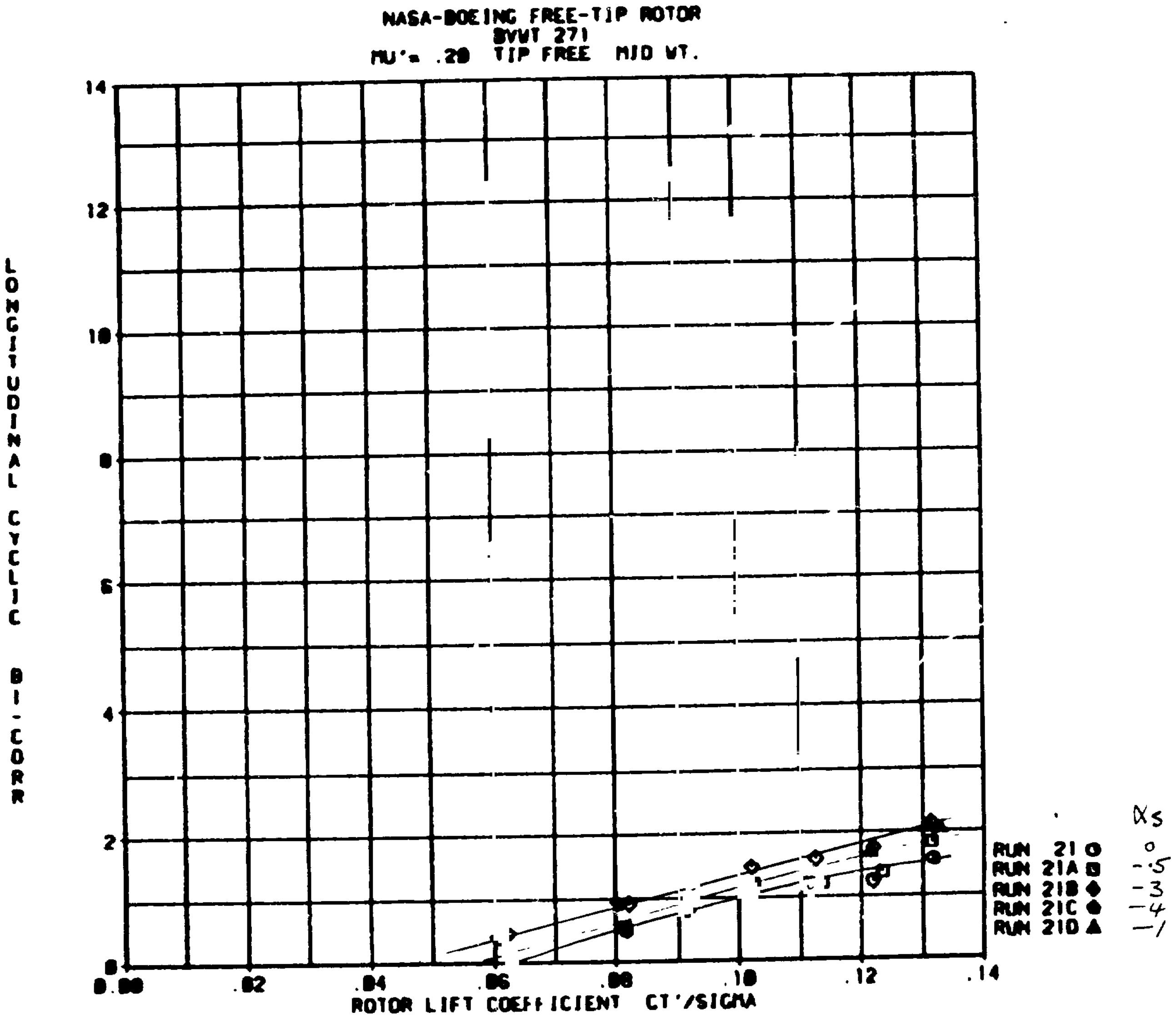
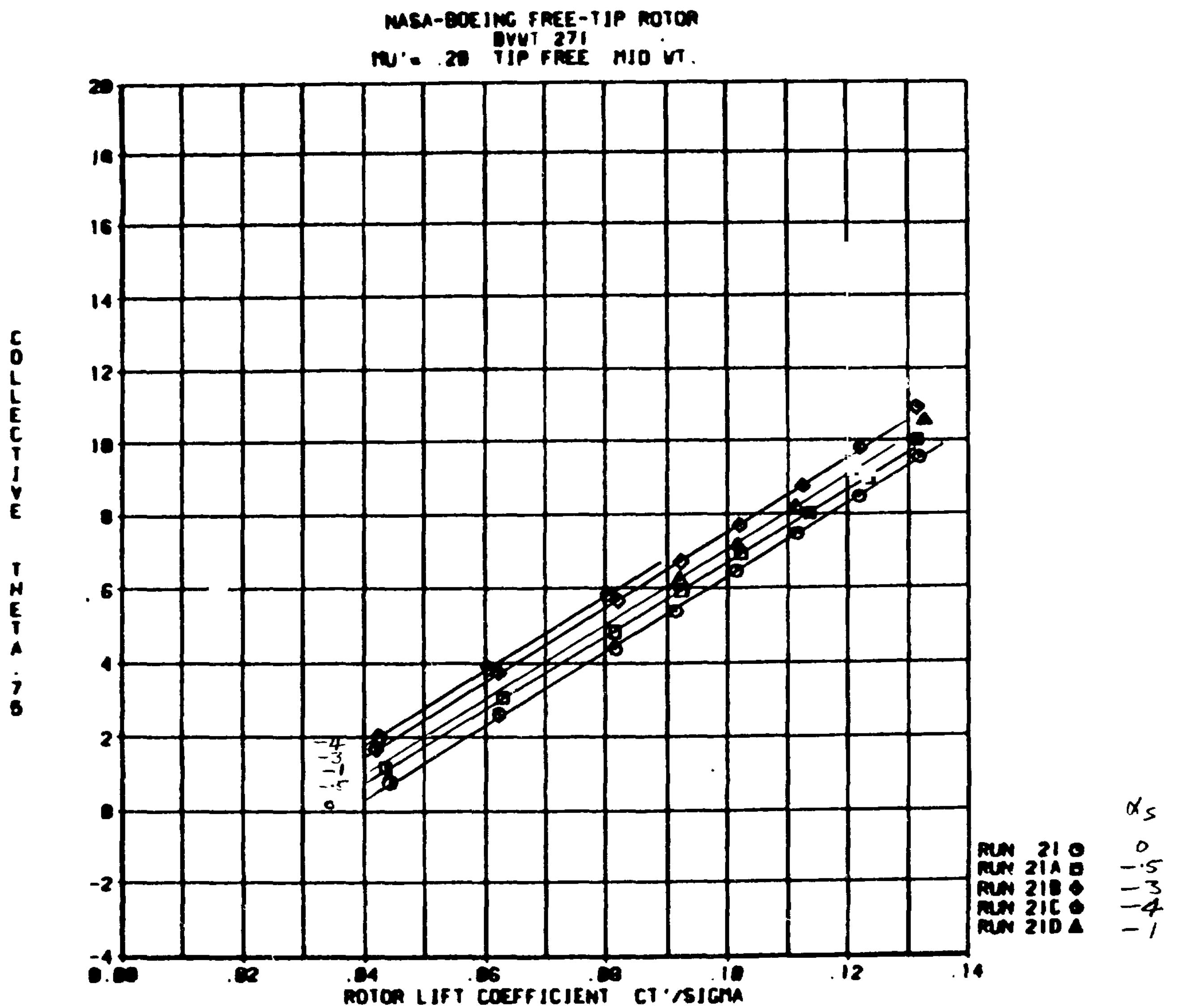



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .20 TIP FREE MID WT.
LONGITUDINAL CYCLIC B1-CORR
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
2
4
6
8
10
12
14
αs
RUN 21 ○ 0
RUN 21A □ -.5
RUN 21B ◆ -3
RUN 21C ● -4
RUN 21D ▲ -1



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ORIGINAL PAGE IS
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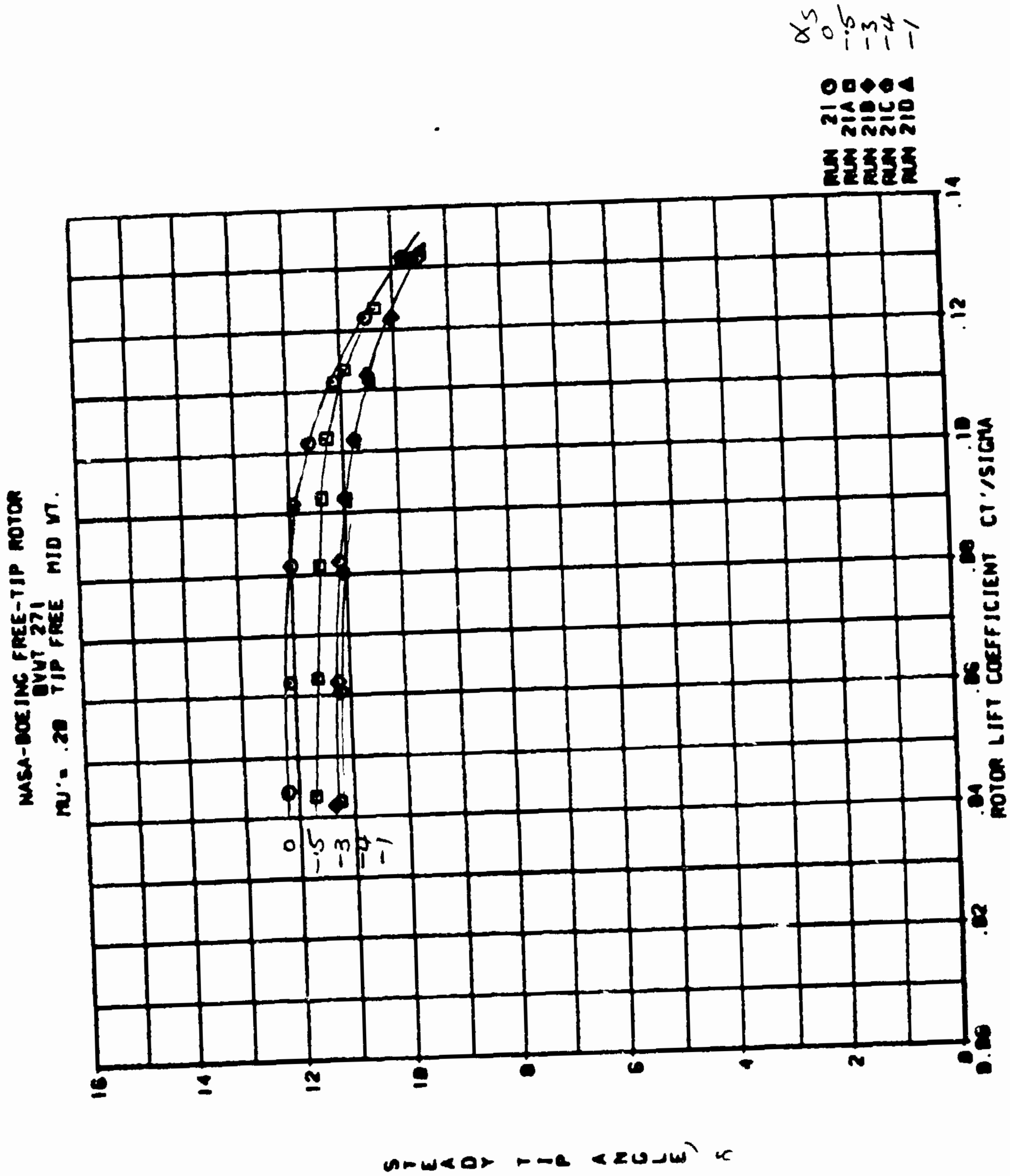

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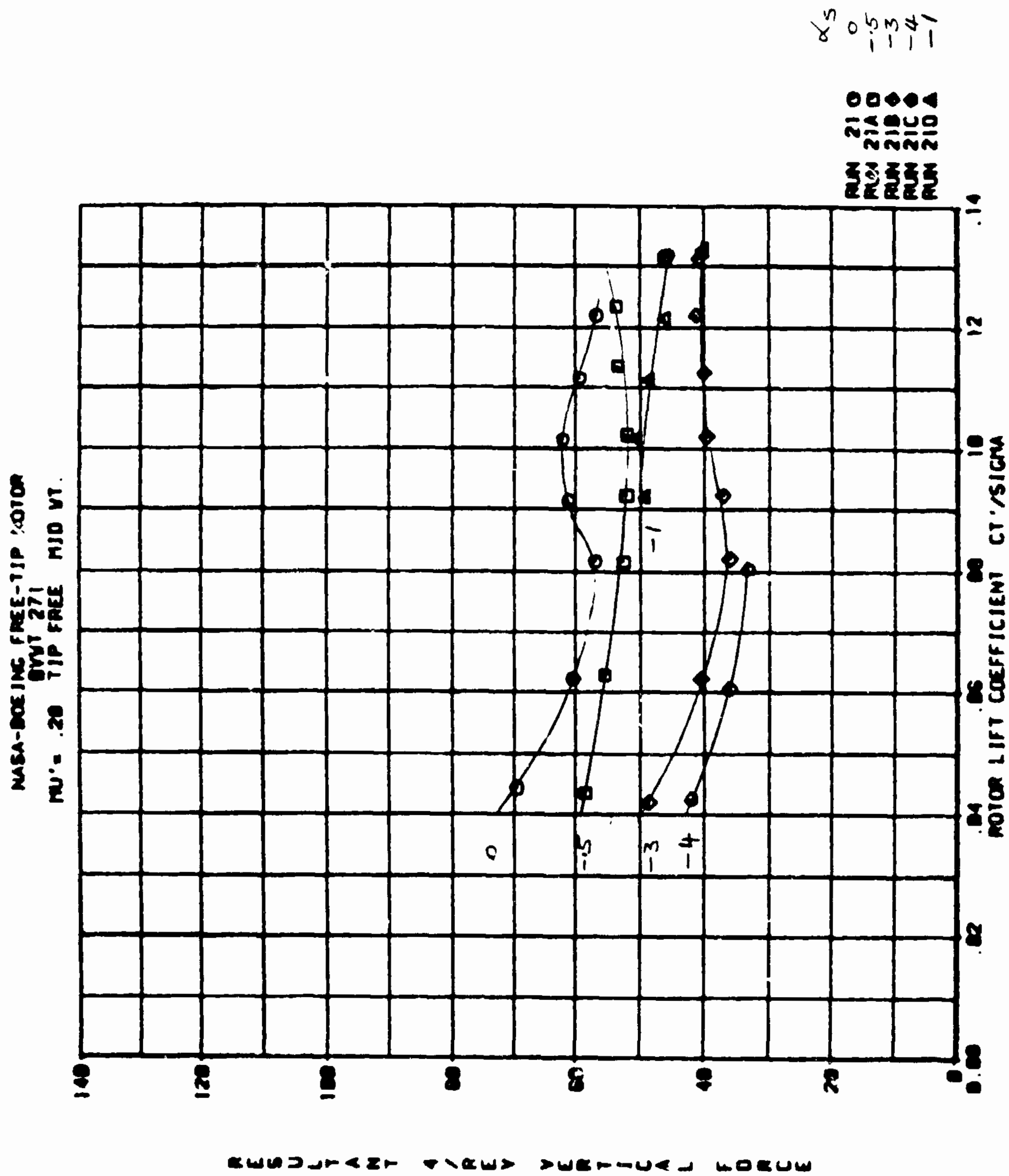
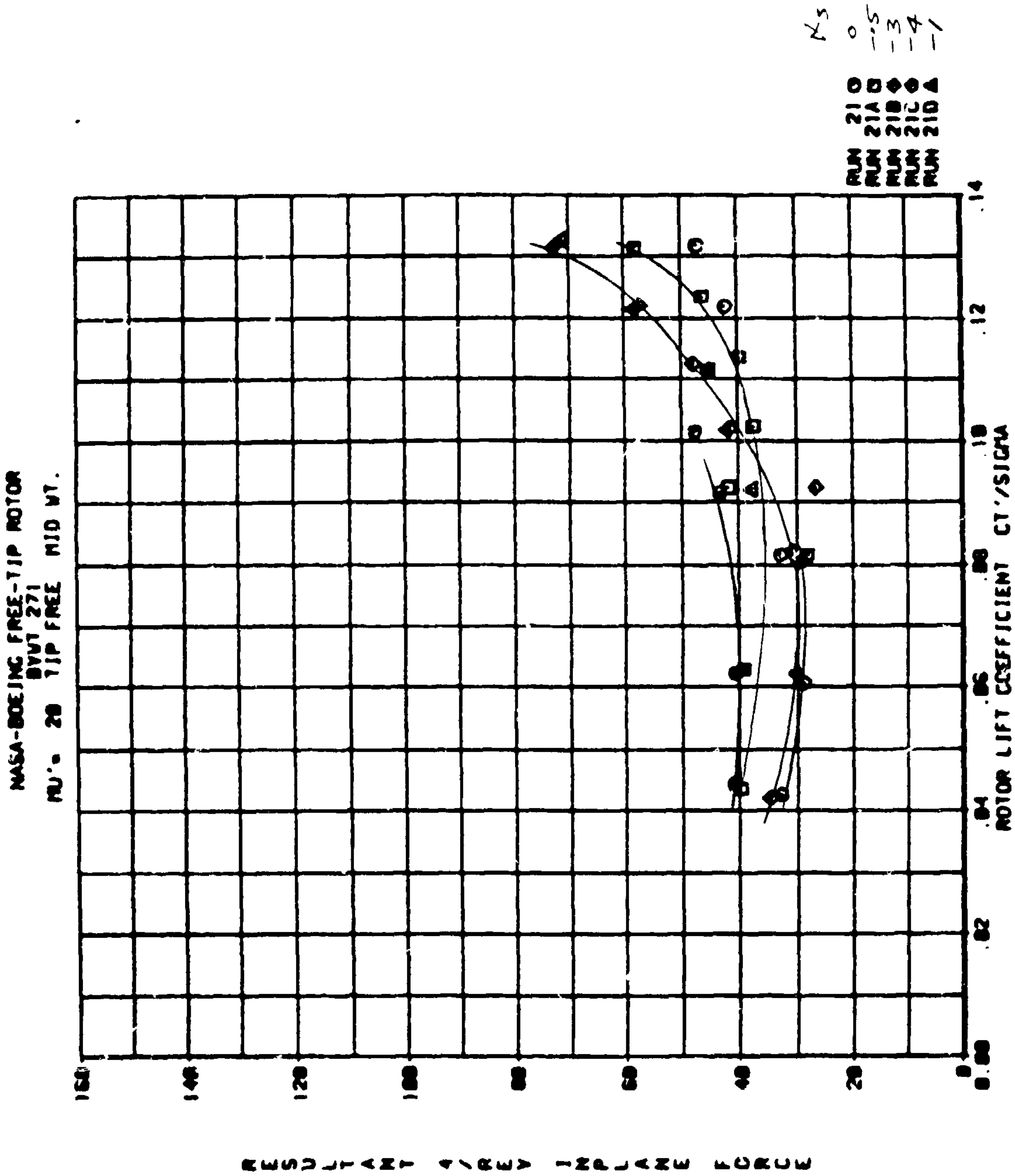
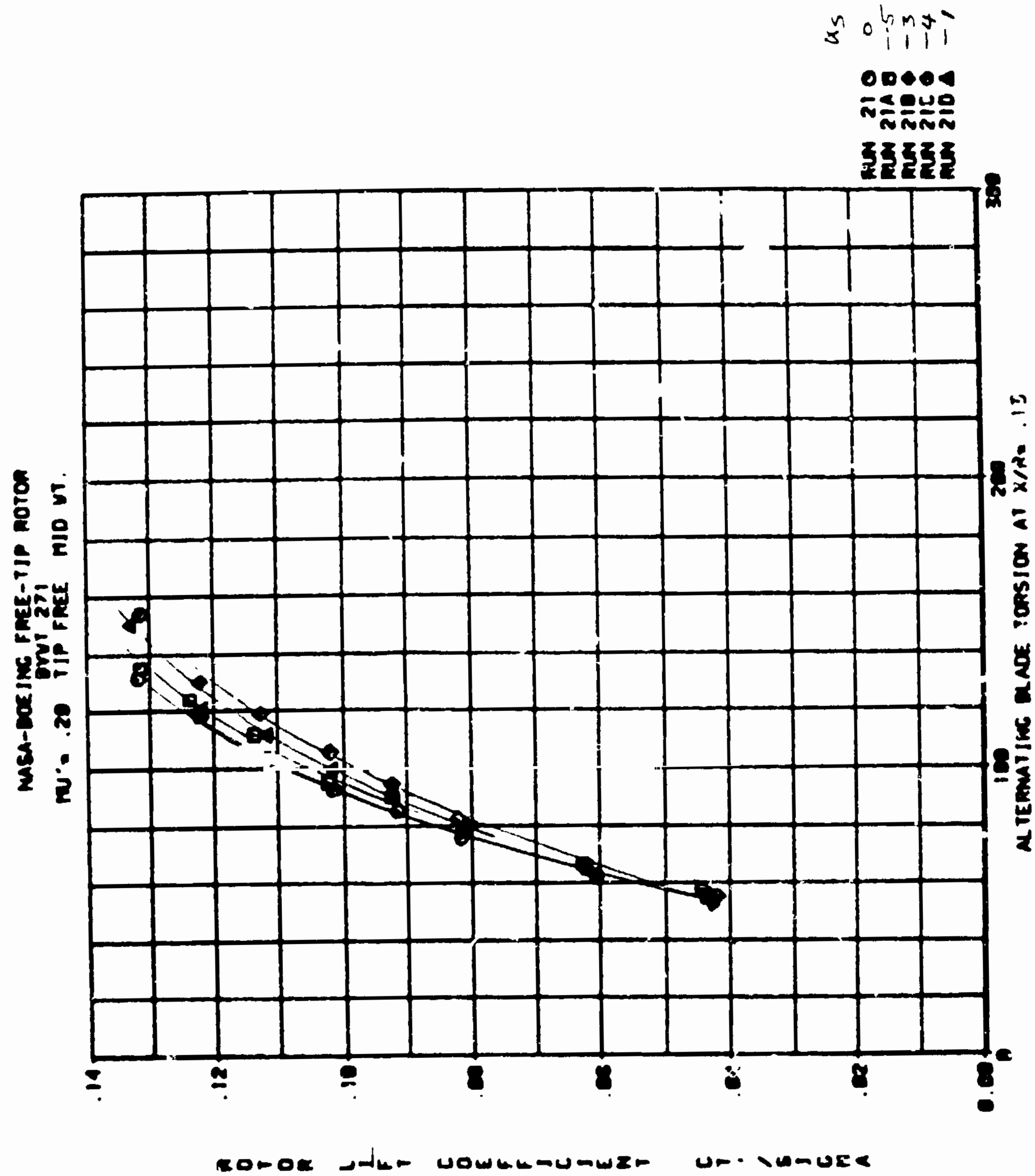



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .20 TIP FREE MID WT.
RUN 21
RUN 21A
RUN 21B
RUN 21C
RUN 21D
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
20
40
60
80
100
120
140
160


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .20 TIP FREE MID WT.
RUN 21
RUN 21A
RUN 21B
RUN 21C
RUN 21D
αs
0
-5
-3
-4
-1
ALTERNATING BLADE TORSION AT X/R= .15
0
100
200
300
.14
.12
.10
.08
.06
.04
.02
0.00

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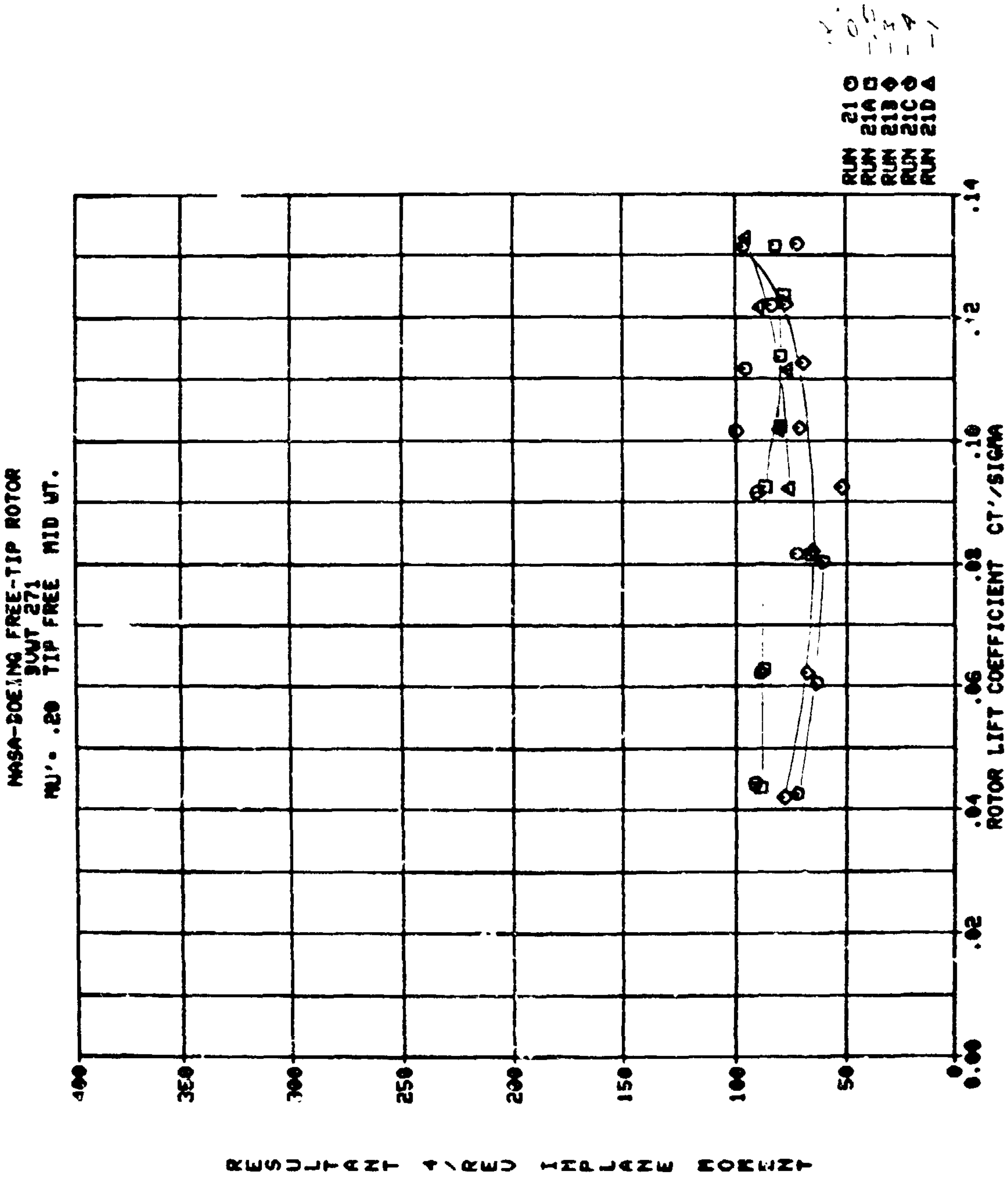

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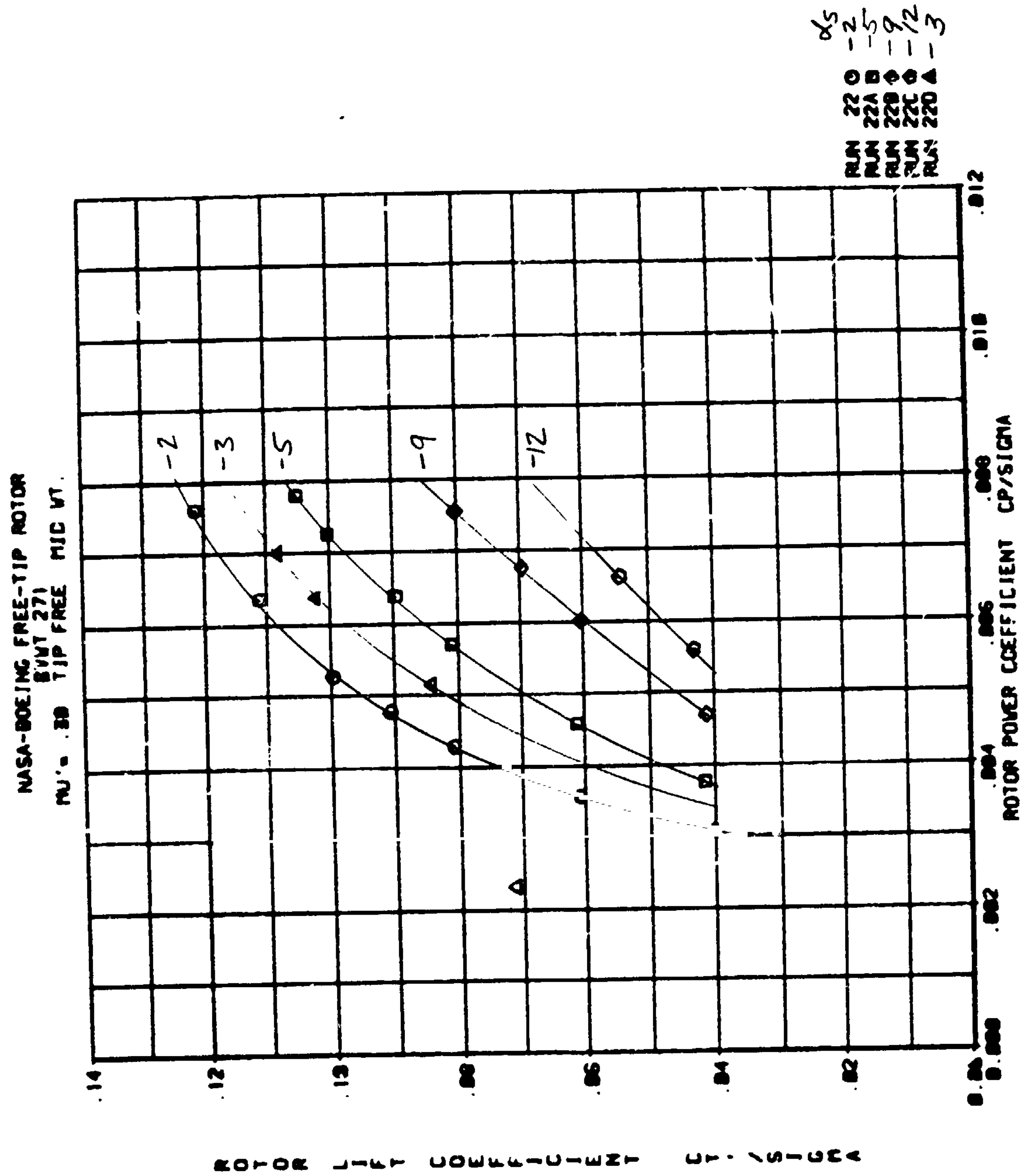

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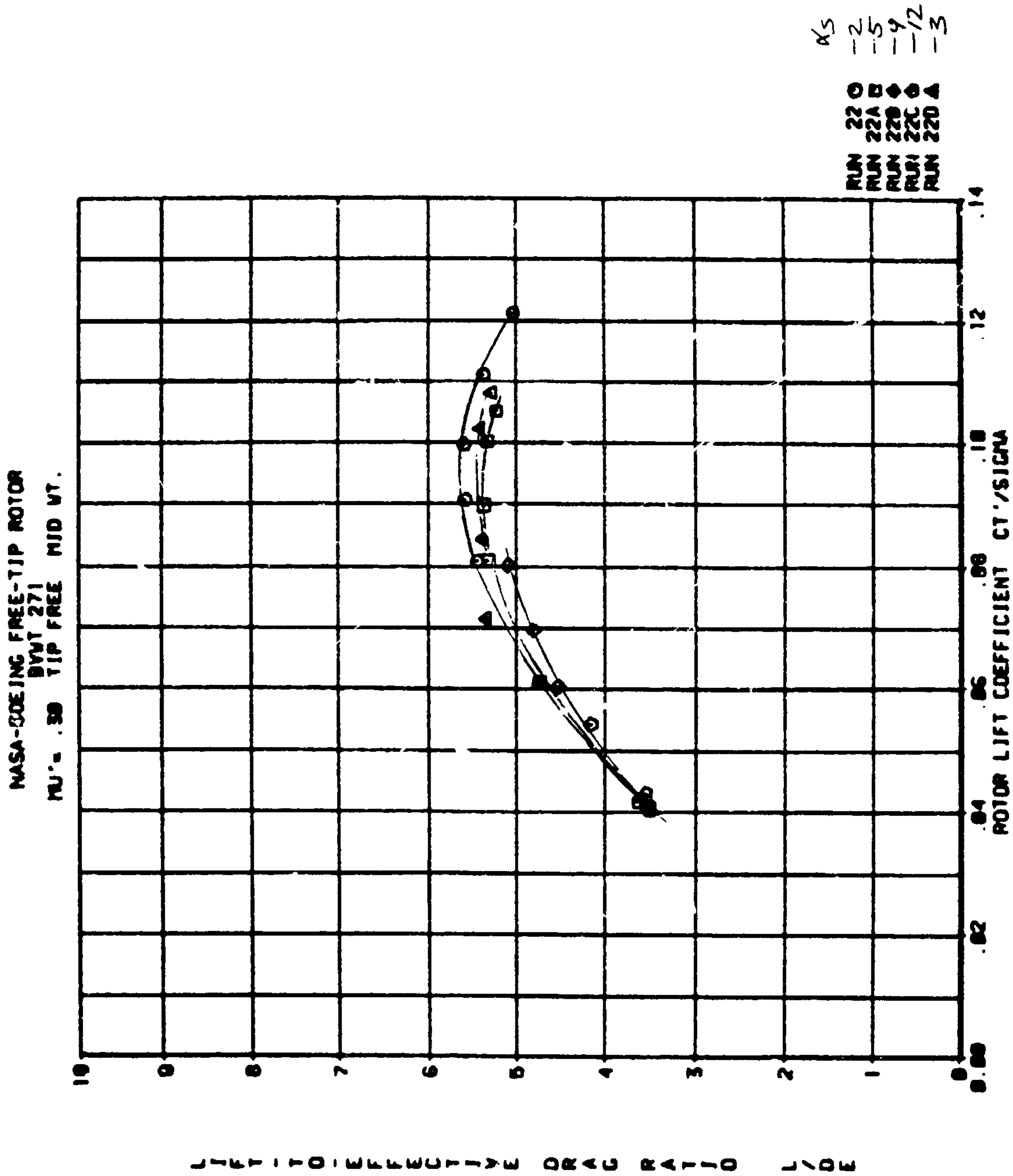
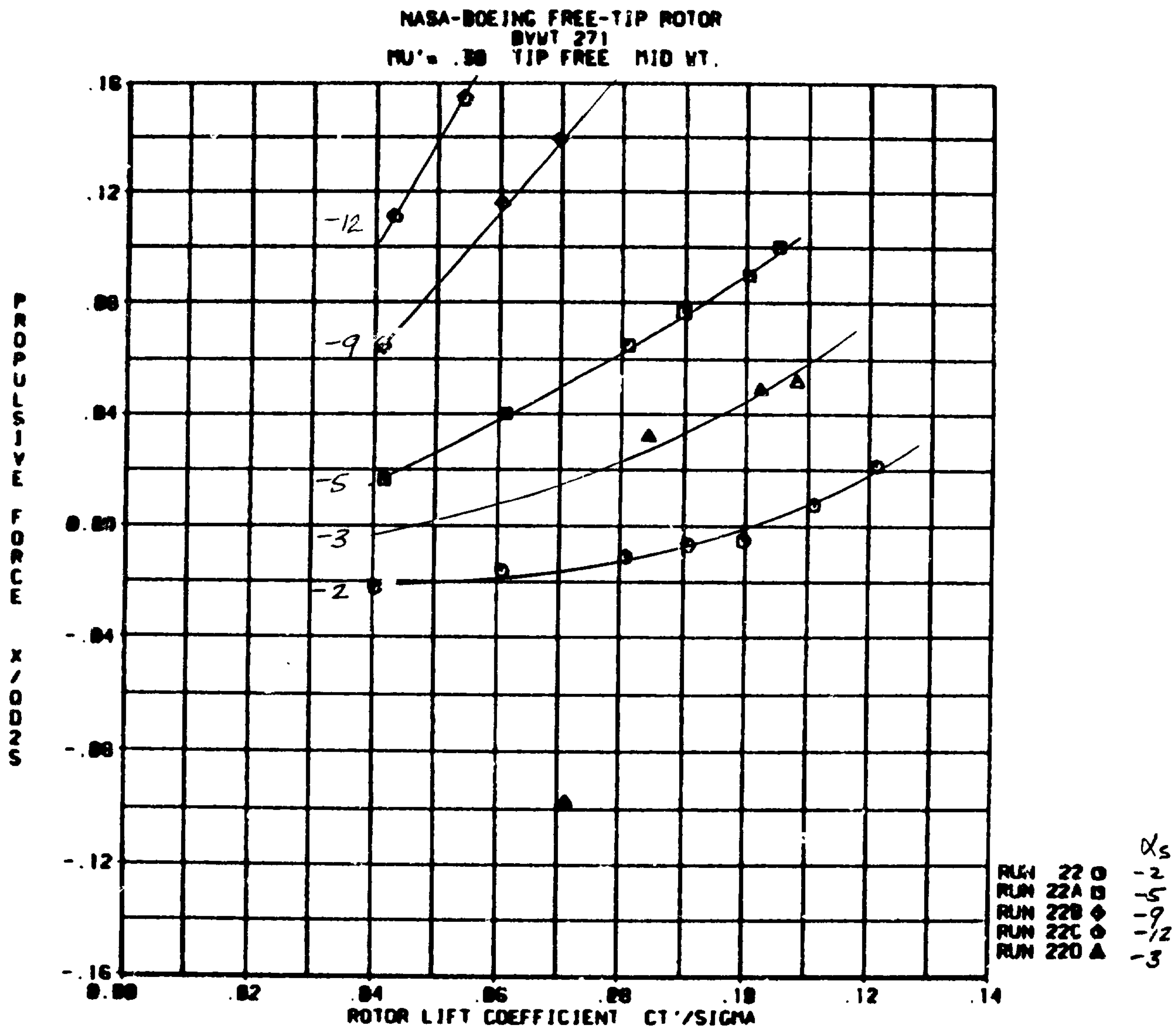
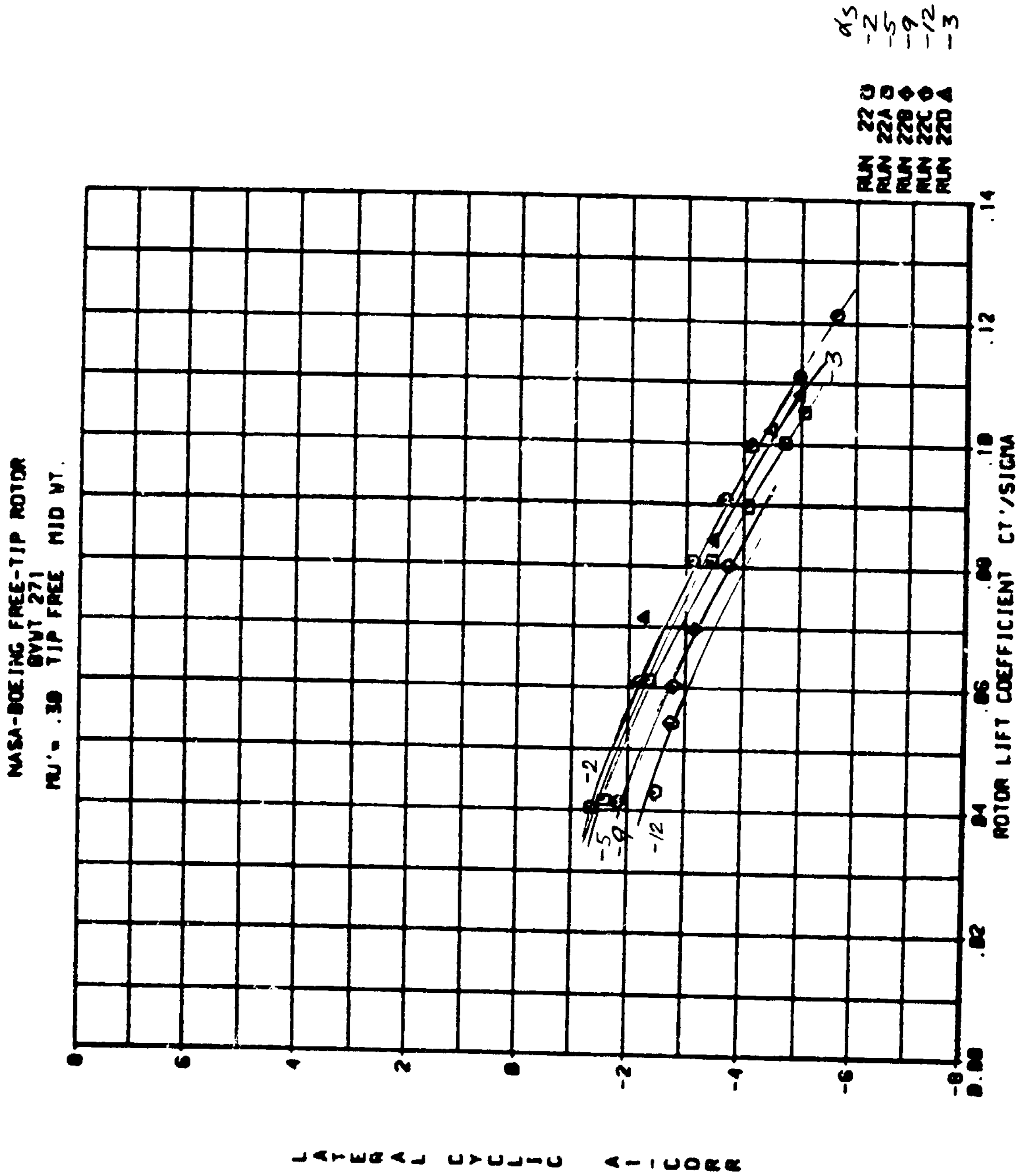
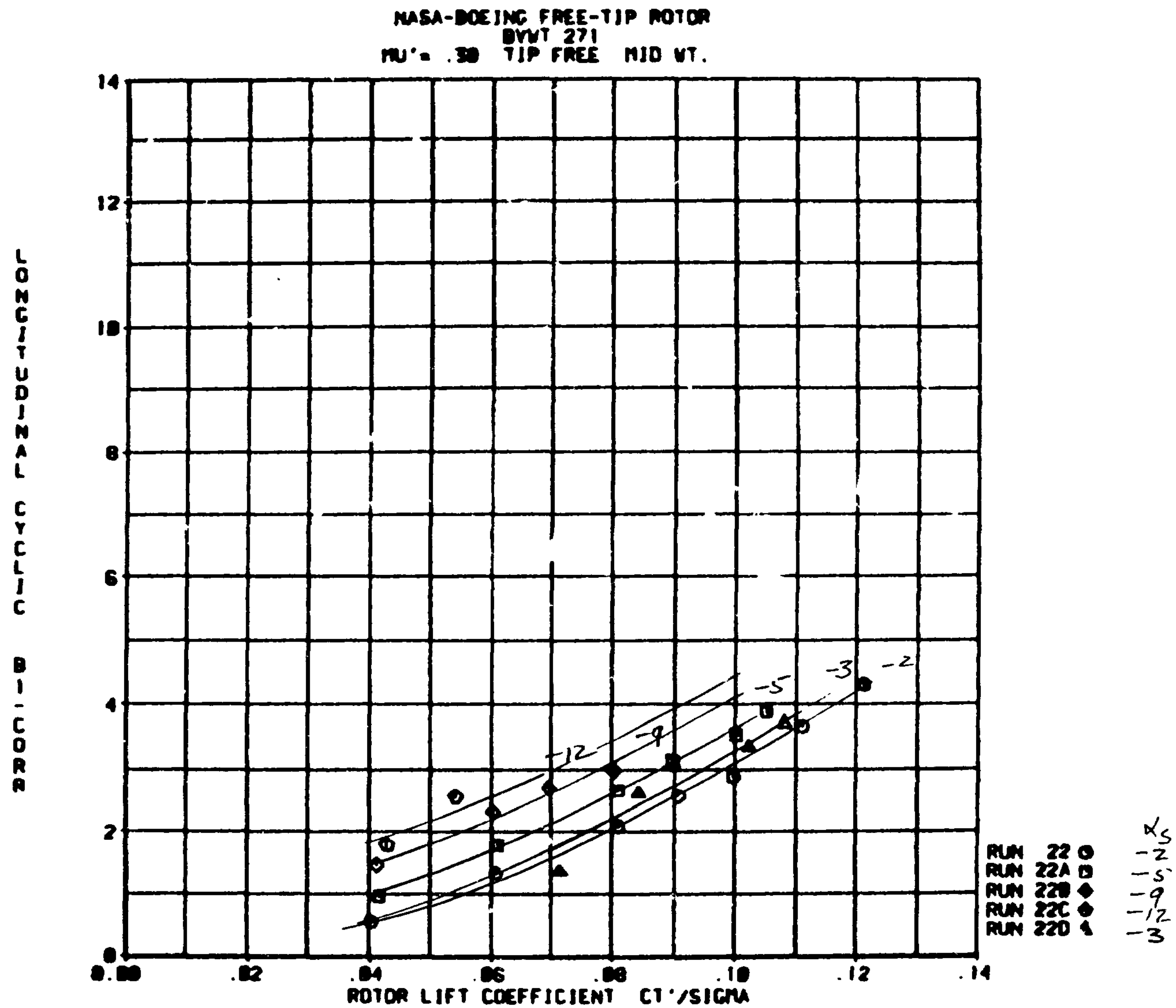



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE MID WT.
PROPULSIVE FORCE X/QD2S
ROTOR LIFT COEFFICIENT CT'/SIGMA
.16
.12
.08
.04
0.00
-.04
-.08
-.12
-.16
.02
.06
.10
.14
-12
-9
-5
-3
-2
α_s
RUN 22 -2
RUN 22A -5
RUN 22B -9
RUN 22C -12
RUN 22D -3


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE MID WT.
ROTOR LIFT COEFFICIENT CT'/SIGMA
RUN 22
RUN 22A
RUN 22B
RUN 22C
RUN 22D
αs
-2
-5
-9
-12
-3
0.00
.02
.04
.06
.08
.10
.12
.14
8
6
4
2
0
-2
-4
-6
-8



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE MID WT.
LONGITUDINAL CYCLIC B1-CORR
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
2
4
6
8
10
12
14
RUN 22
RUN 22A
RUN 22B
RUN 22C
RUN 22D
α_S
-2
-5
-9
-12
-3

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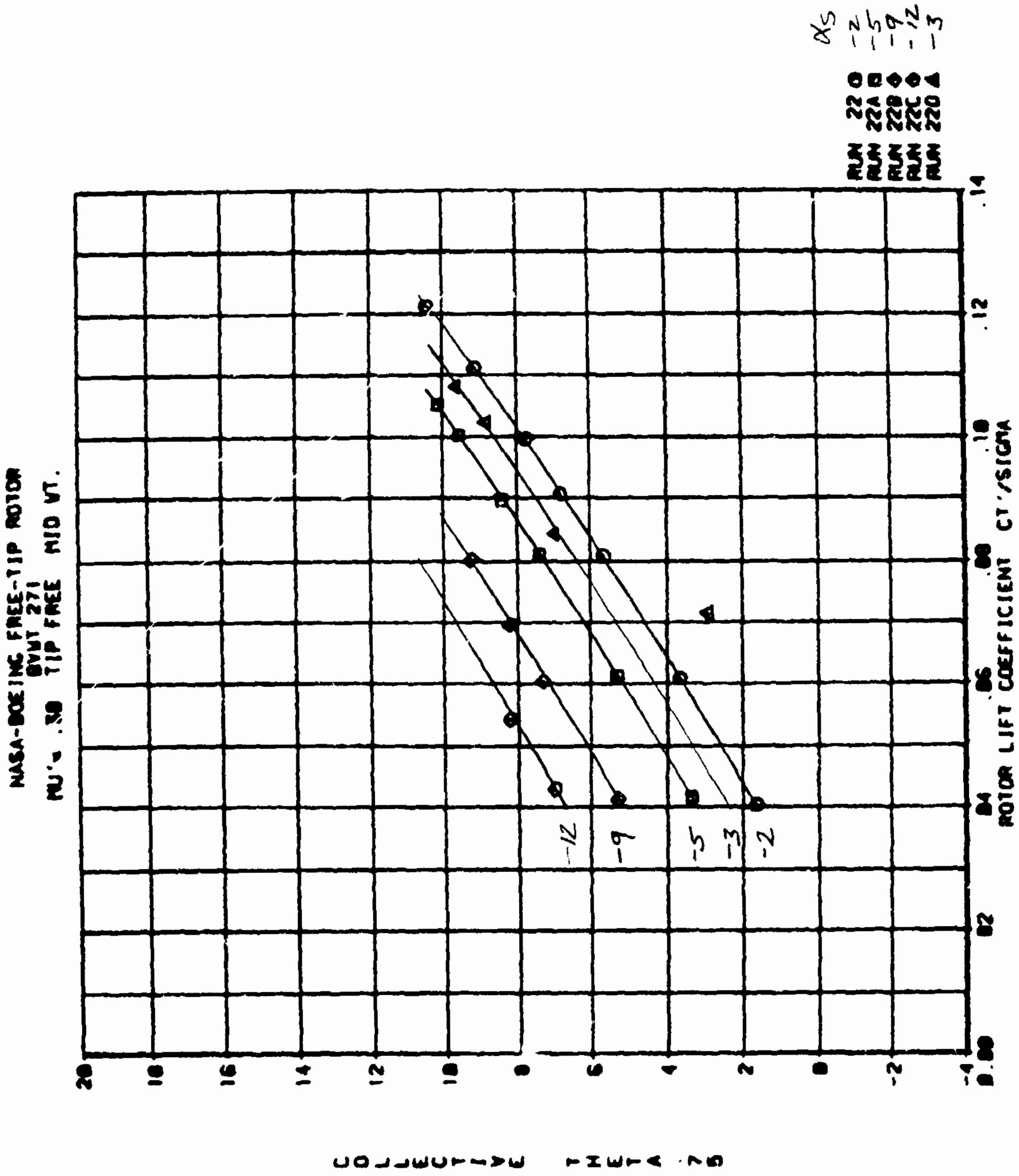

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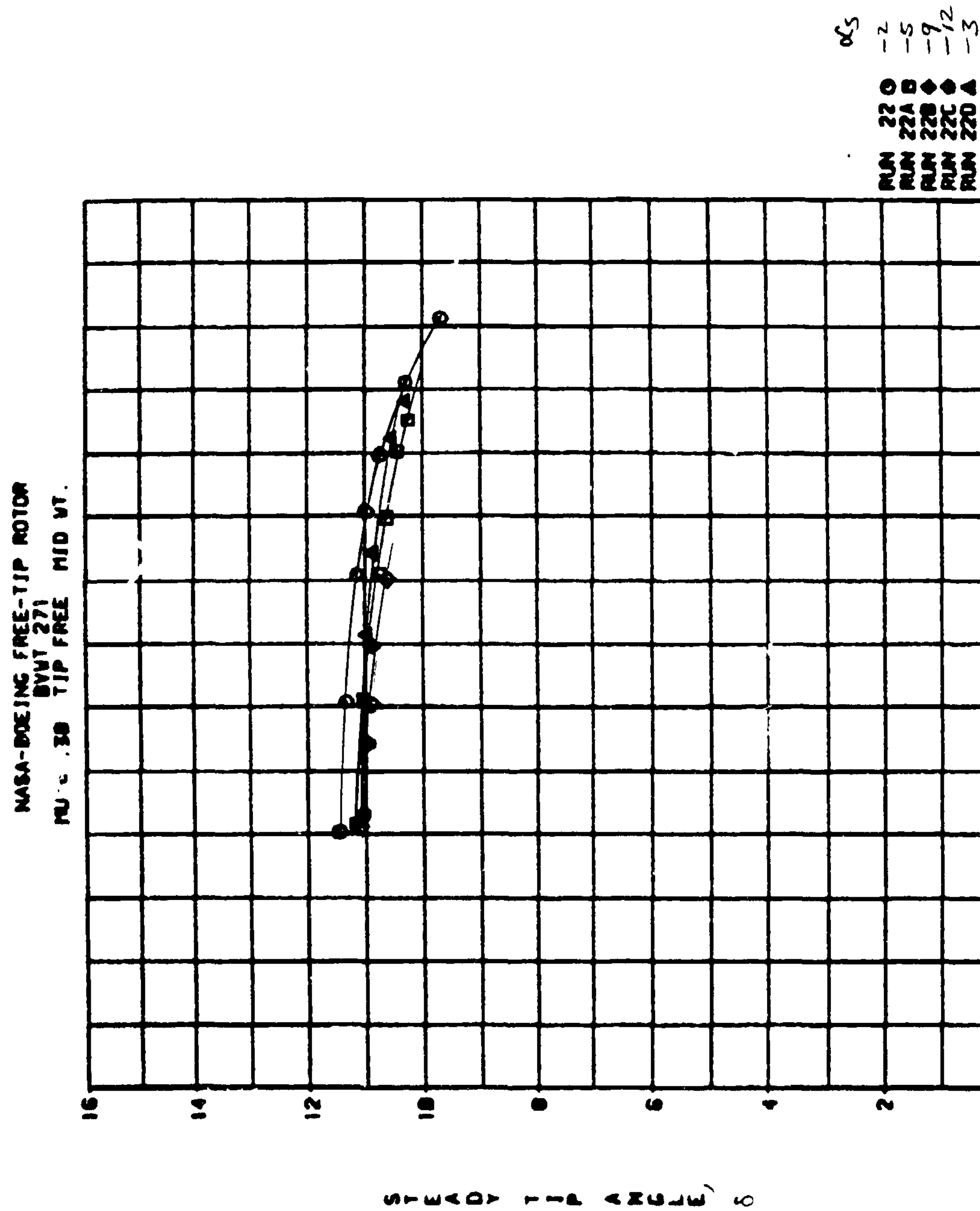

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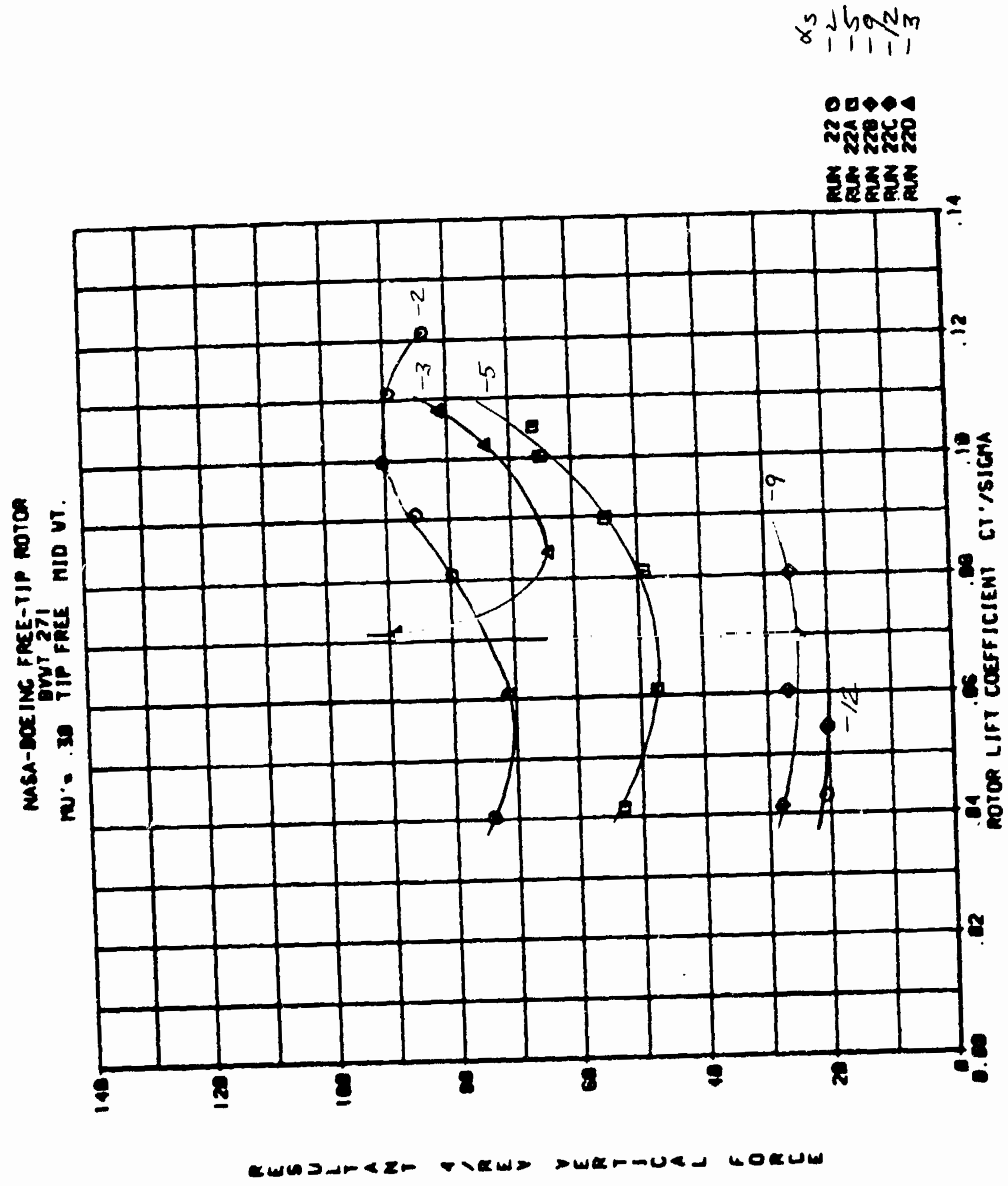

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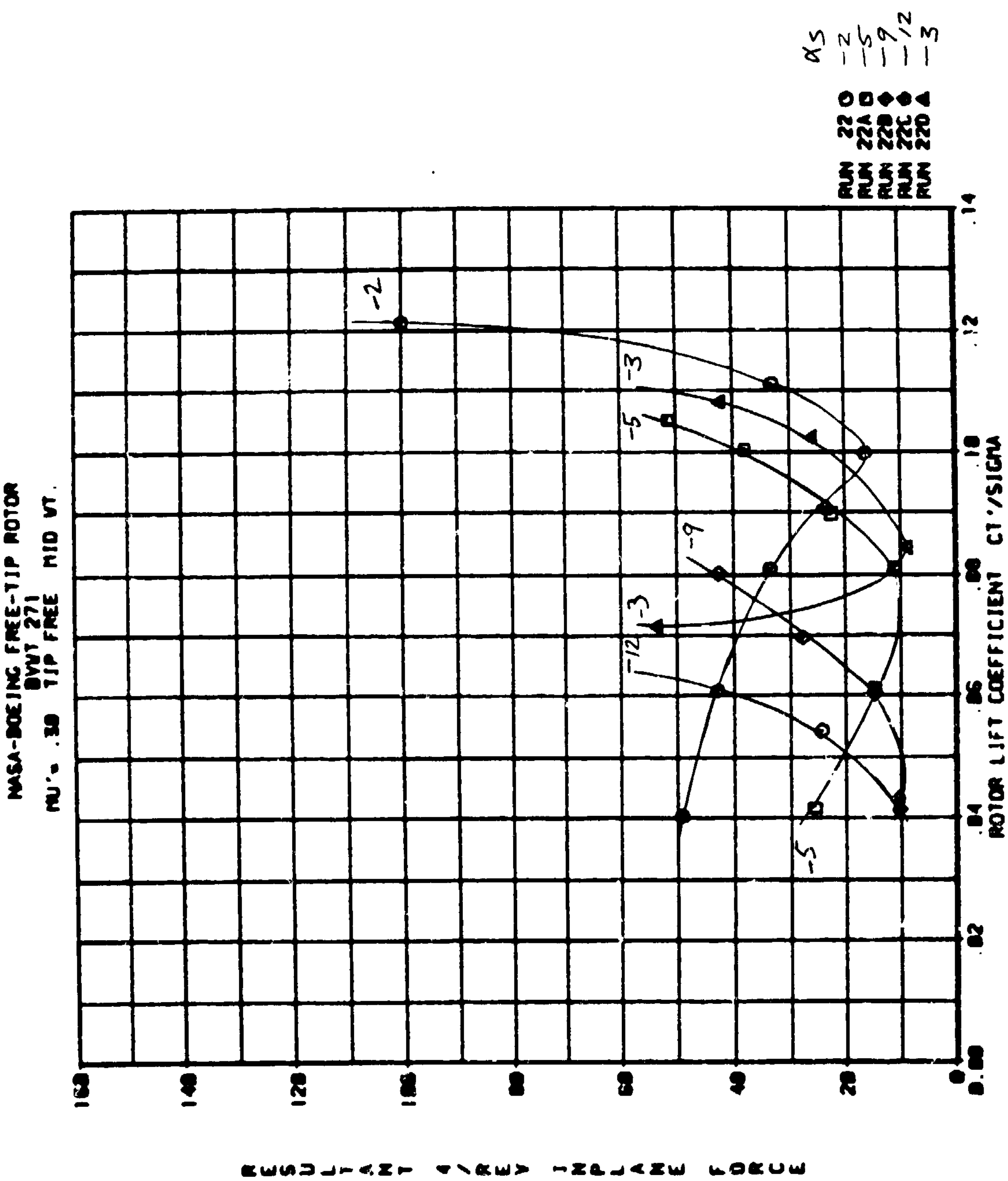

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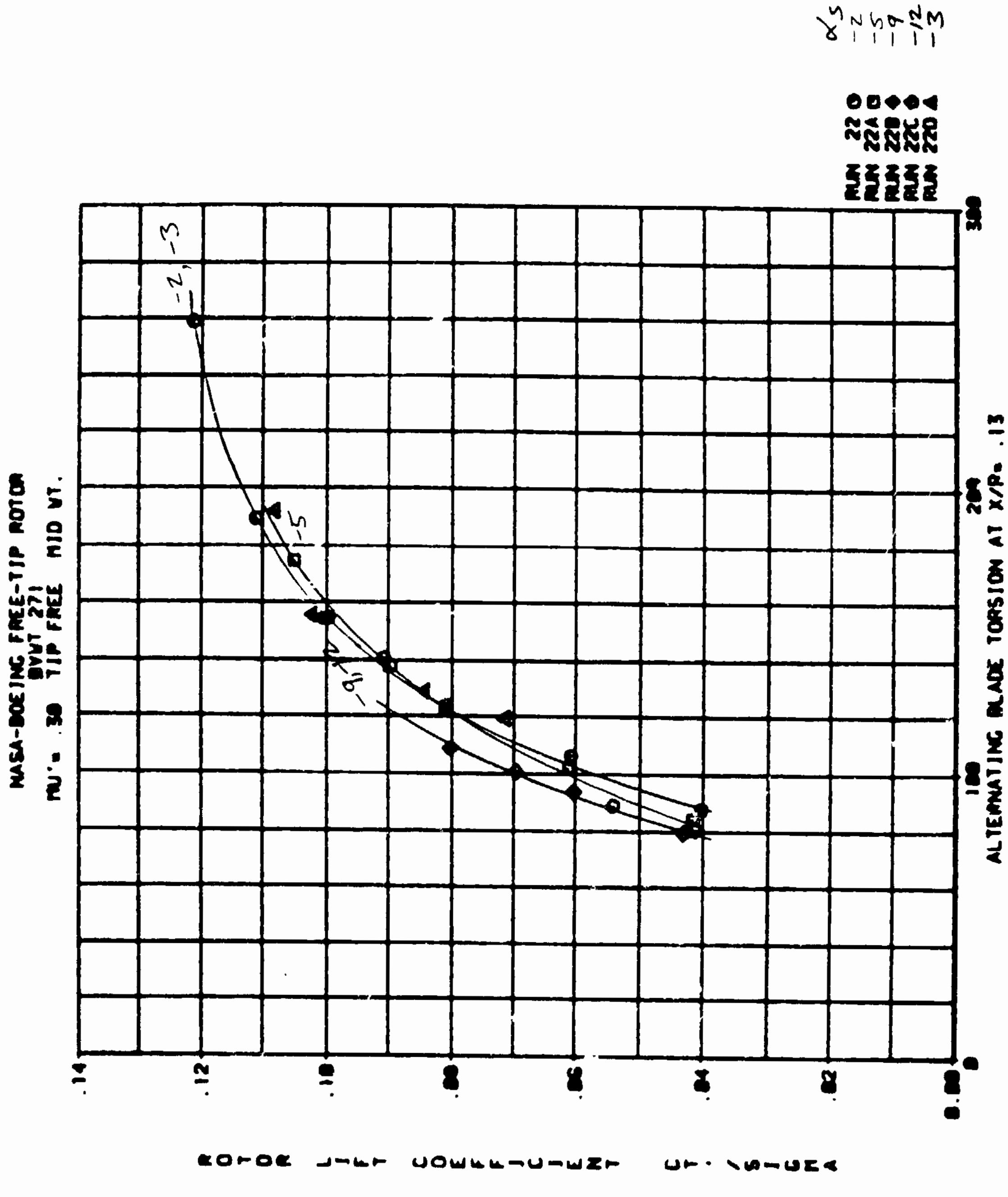

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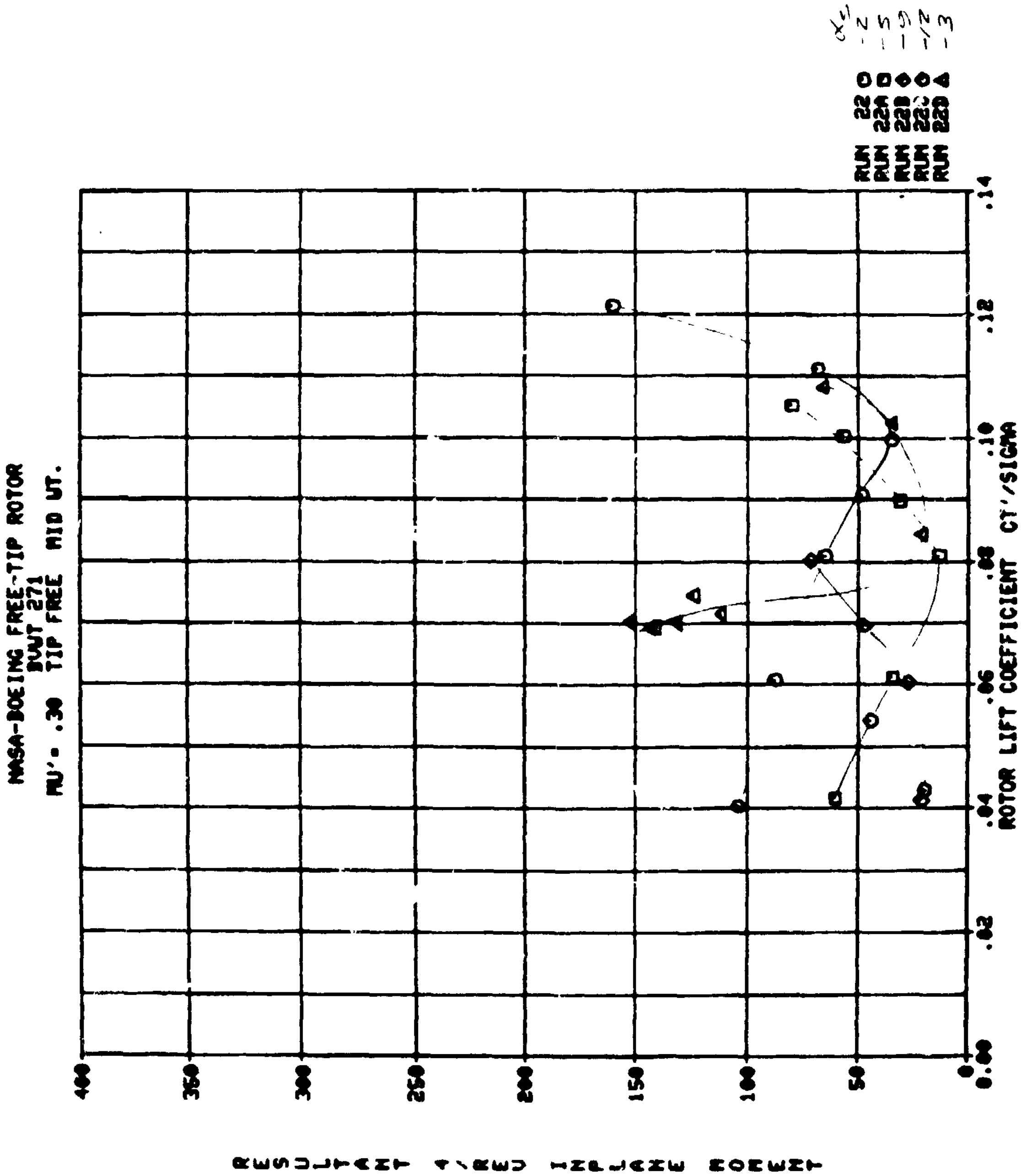

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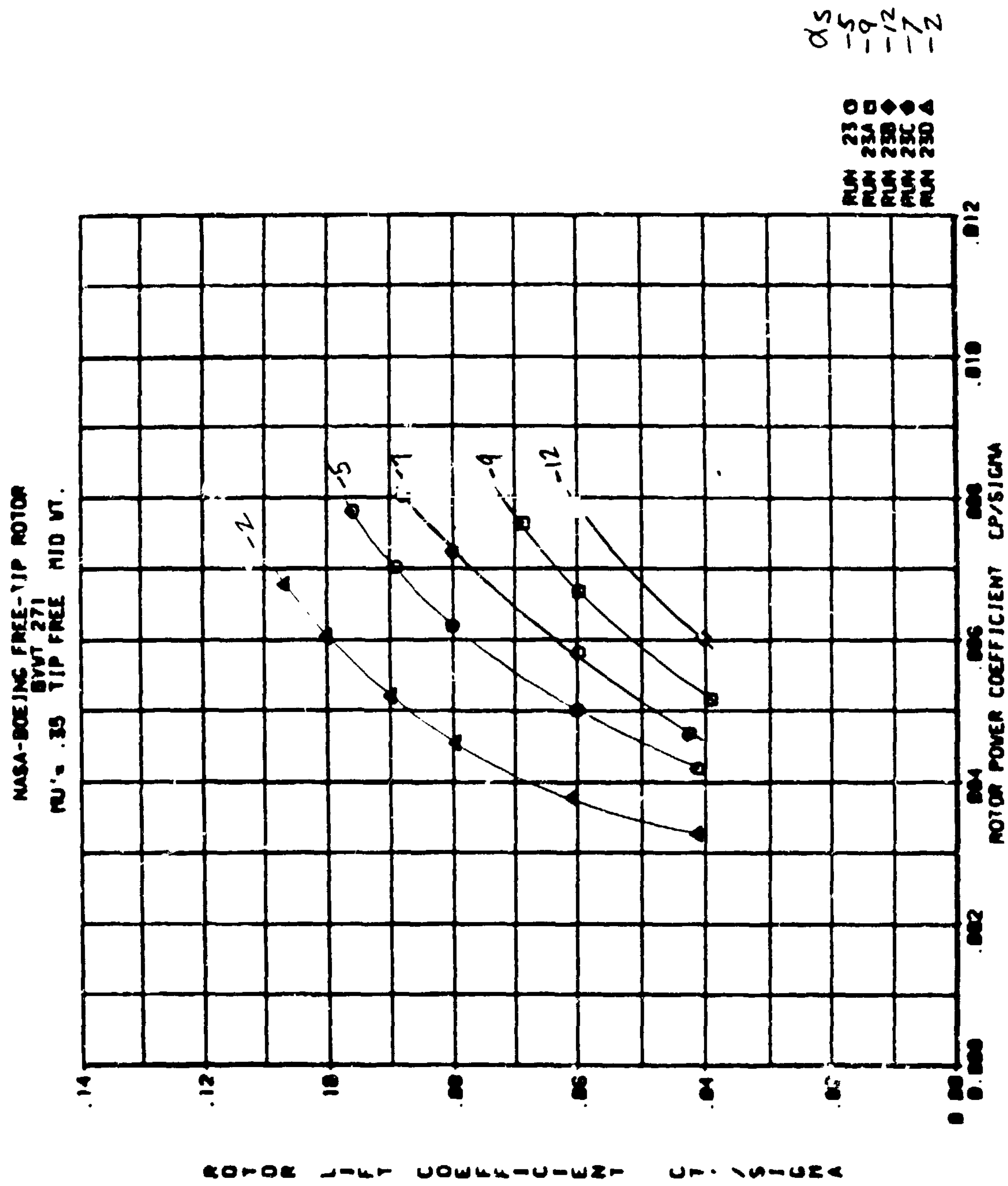

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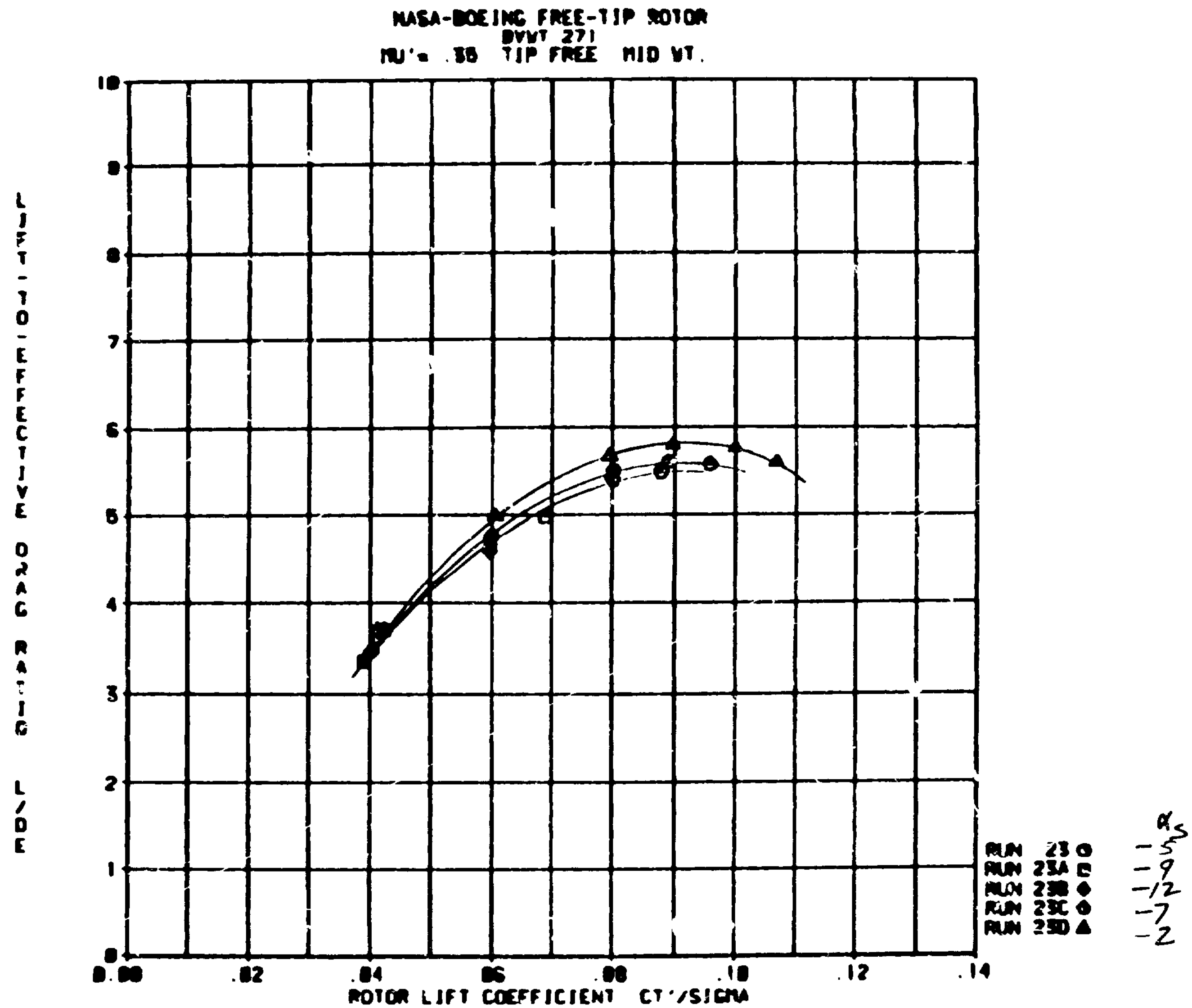

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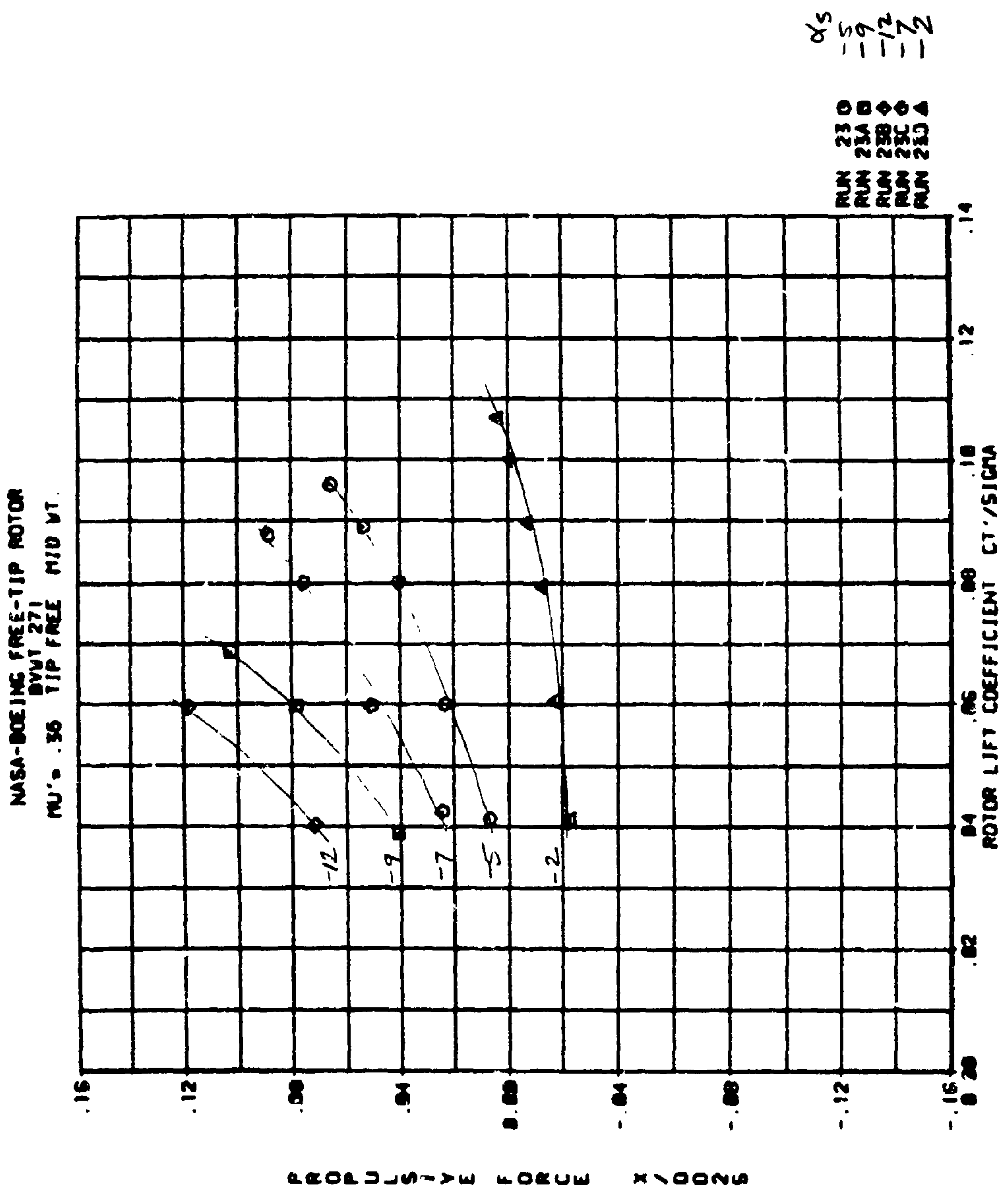
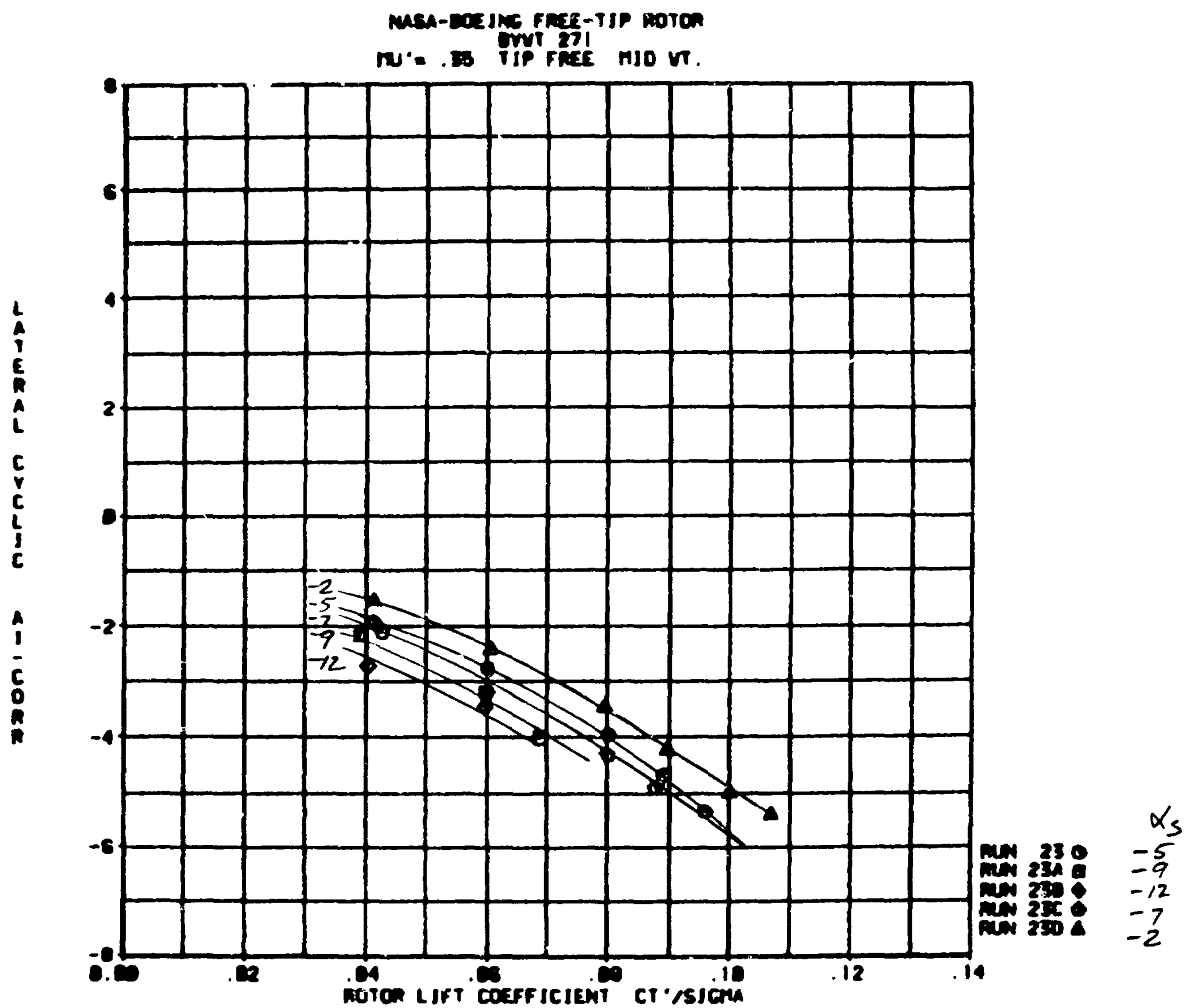
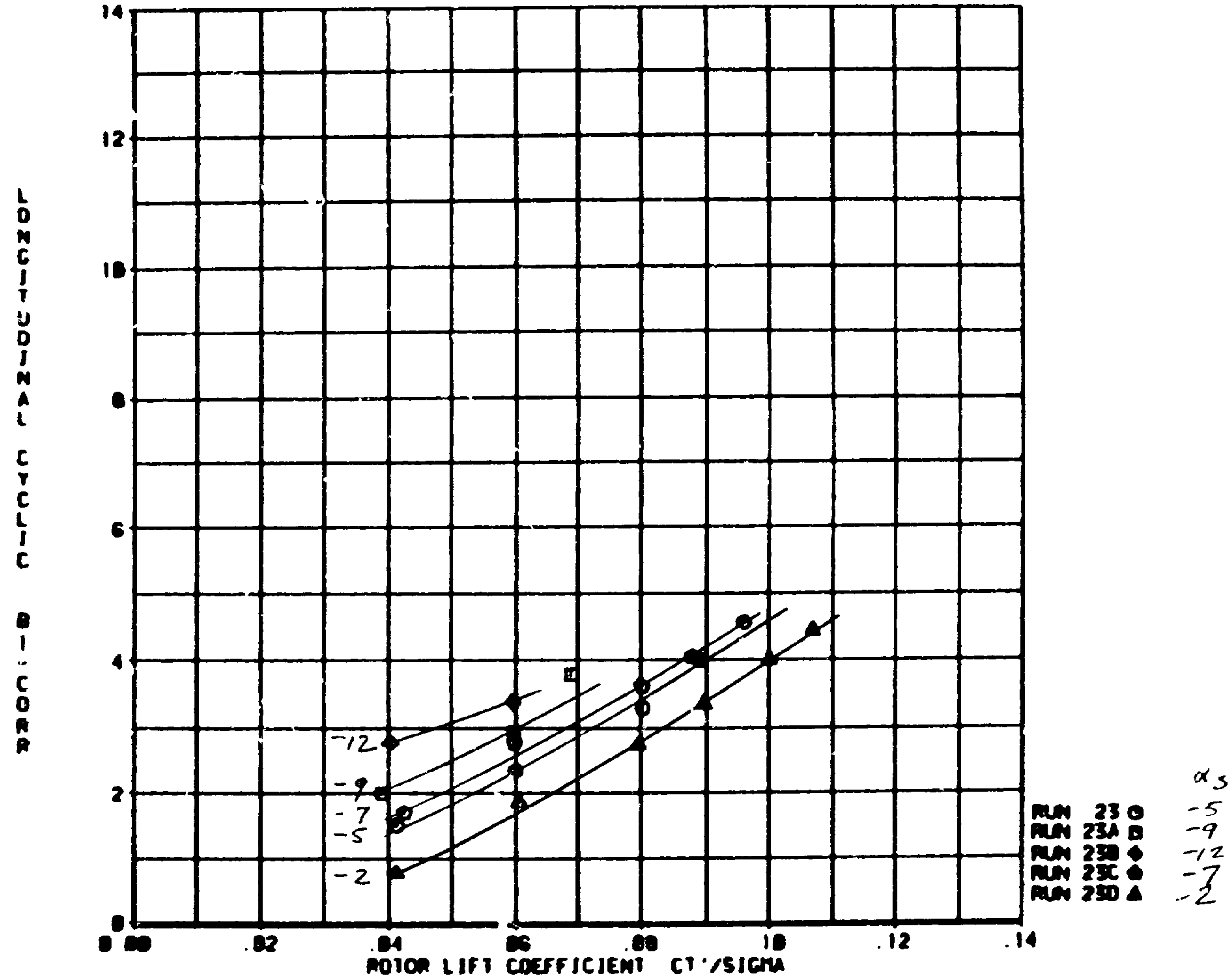



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FREE MID VT.
LATERAL CYCLIC A1-CORR
ROTOR LIFT COEFFICIENT CT'/SIGMA
8
6
4
2
0
-2
-4
-6
-8
0.00
.02
.04
.06
.08
.10
.12
.14
RUN 23 -5
RUN 23A -9
RUN 23B -12
RUN 23C -7
RUN 23D -2
α_s
-2
-5
-7
-9
-12

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .35 TIP FREE MID WT.



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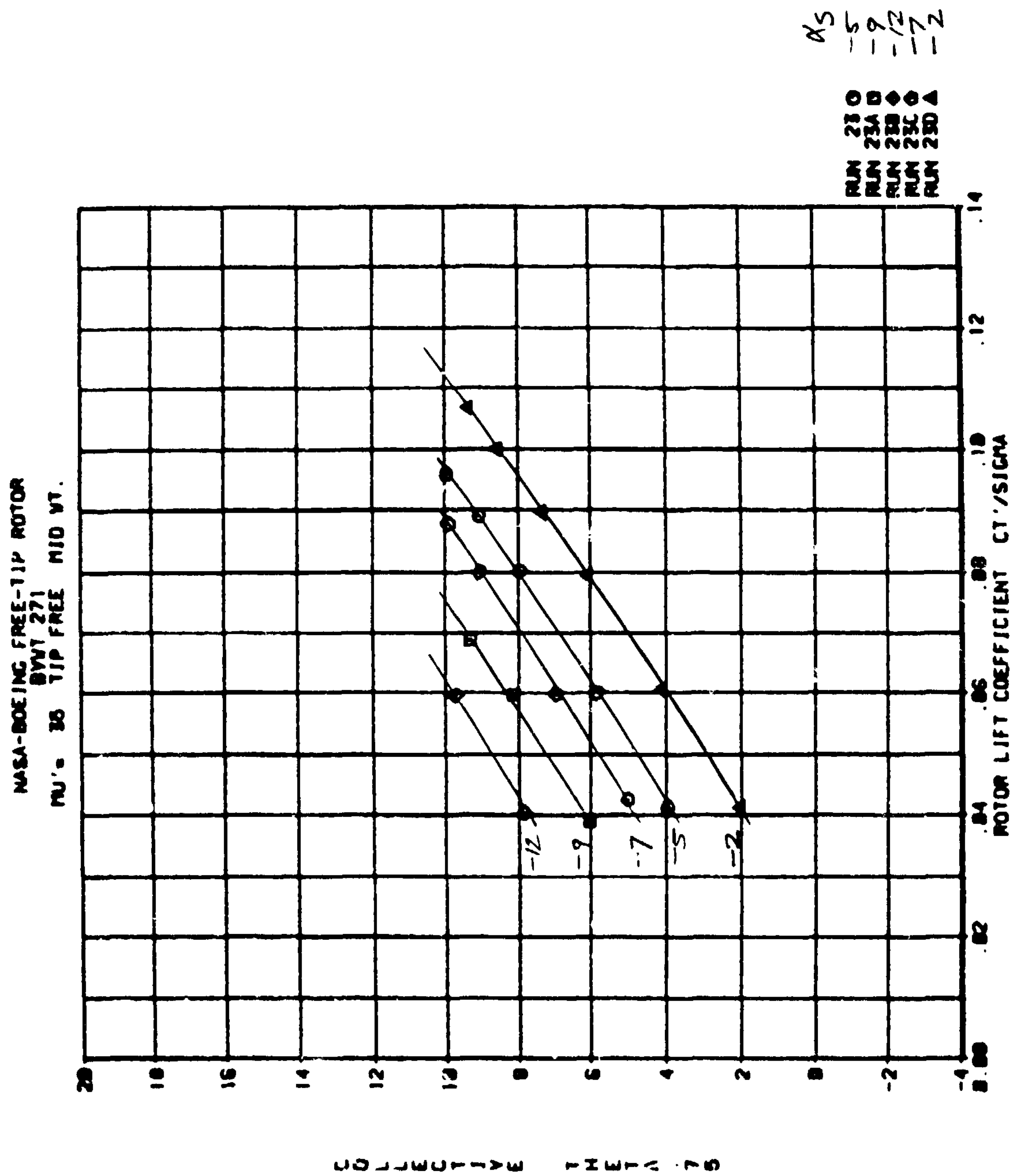

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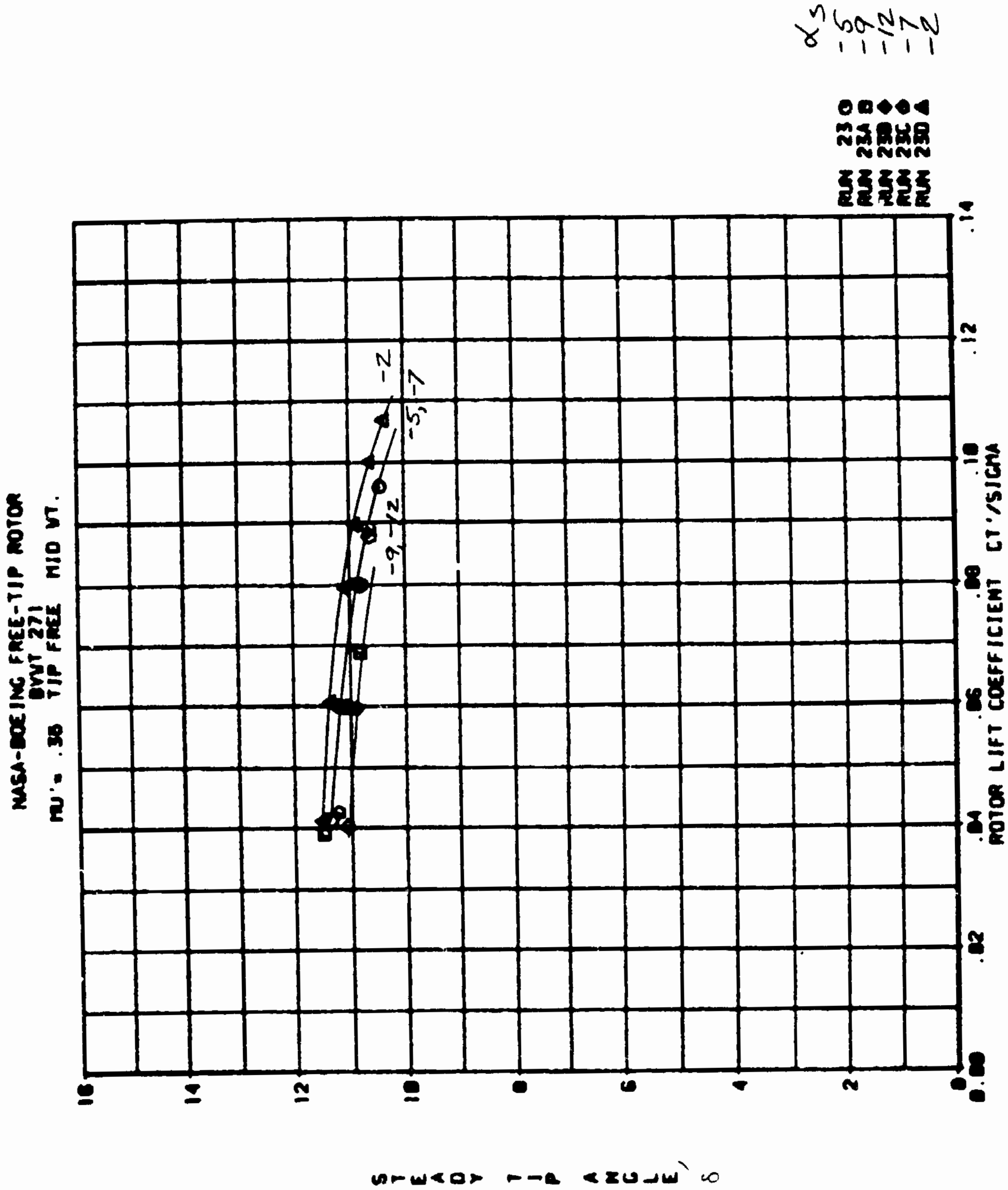

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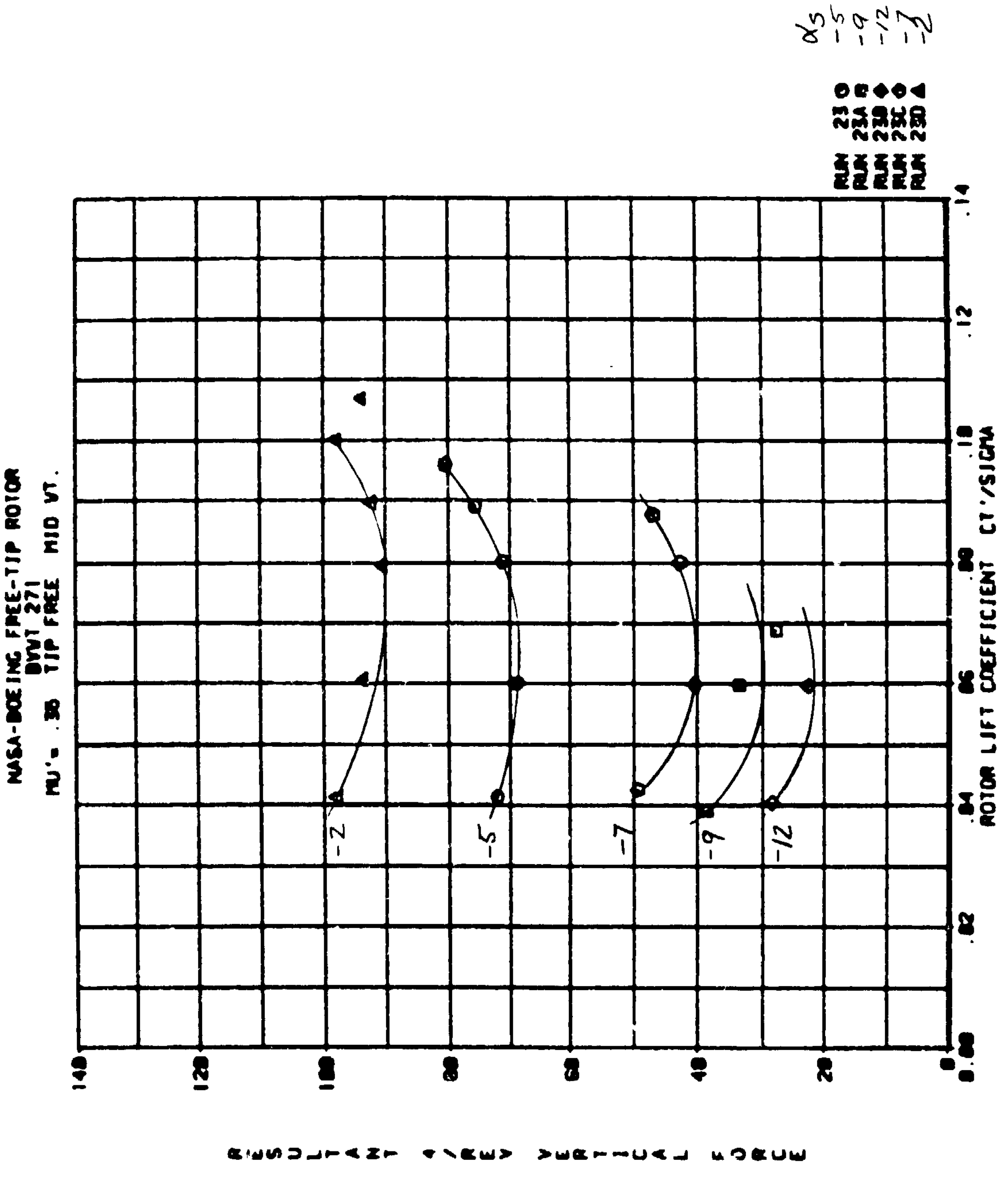

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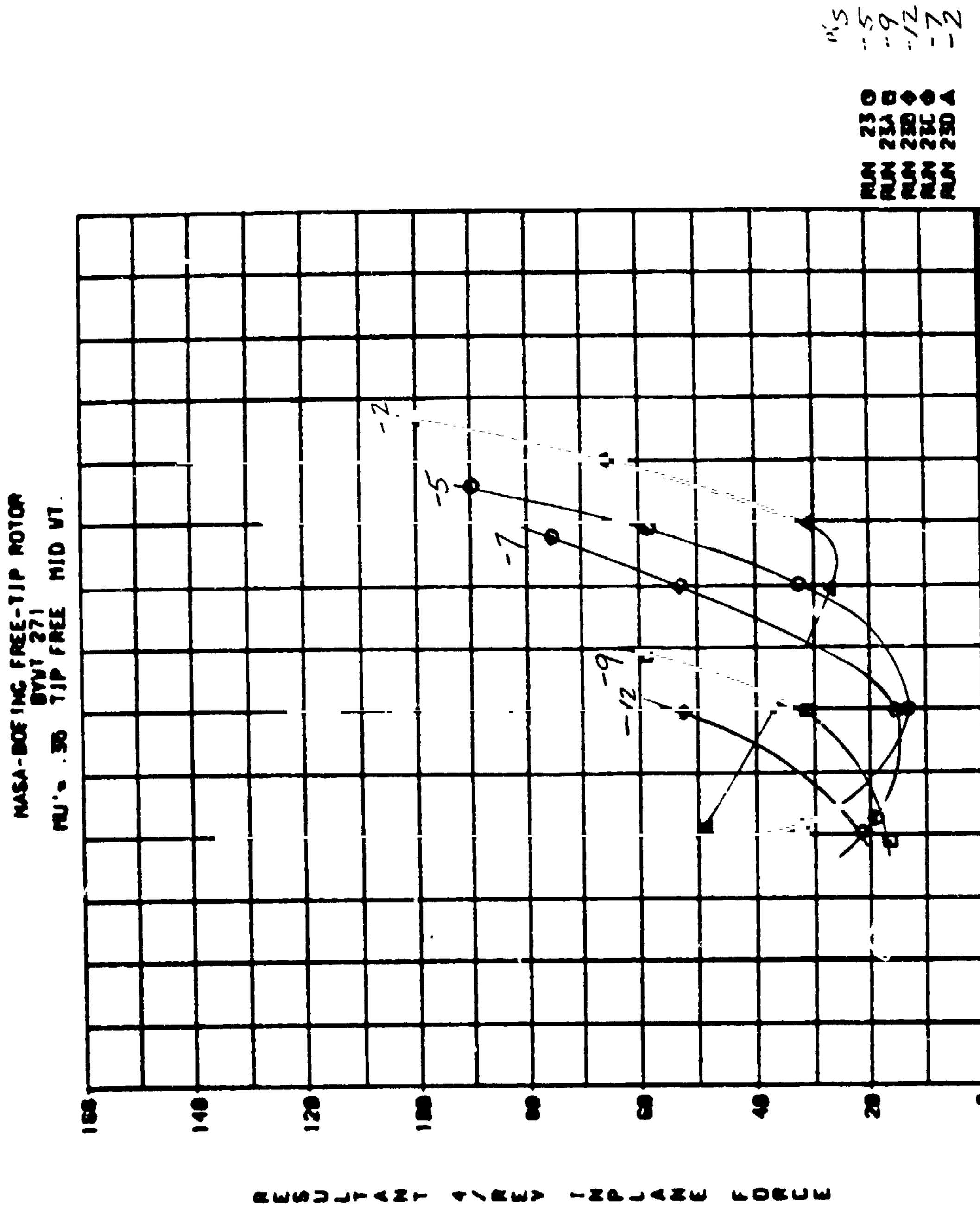

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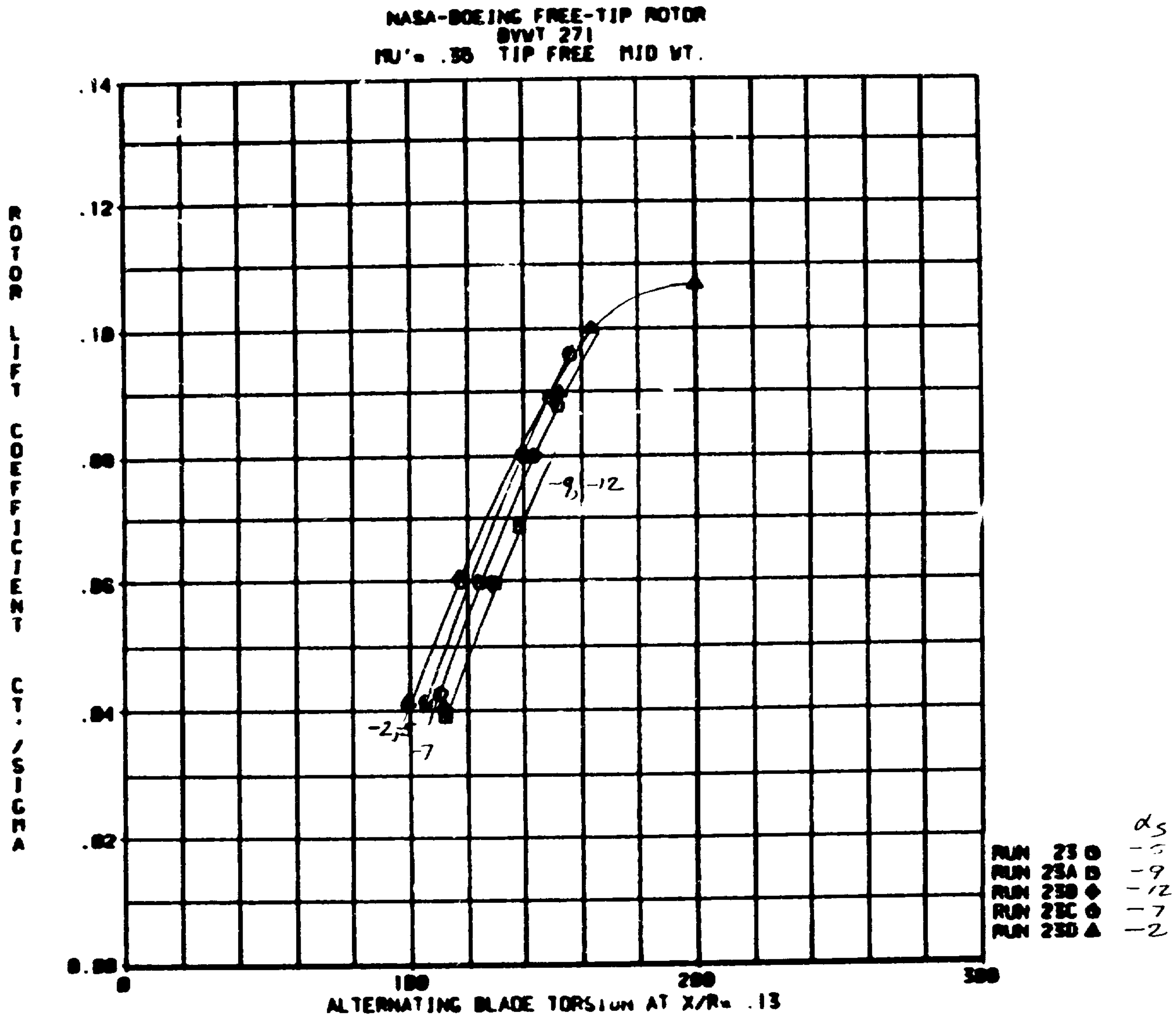

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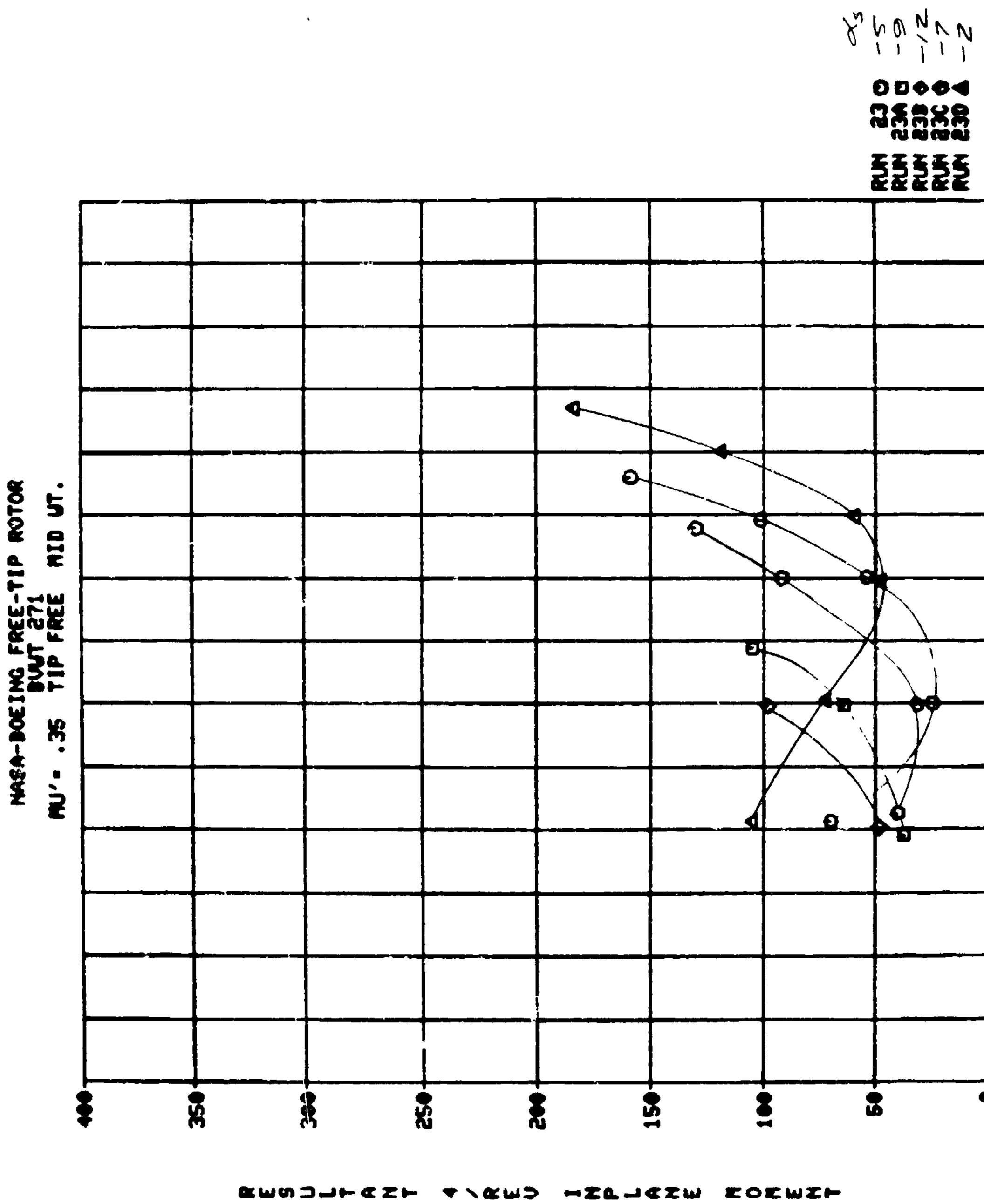

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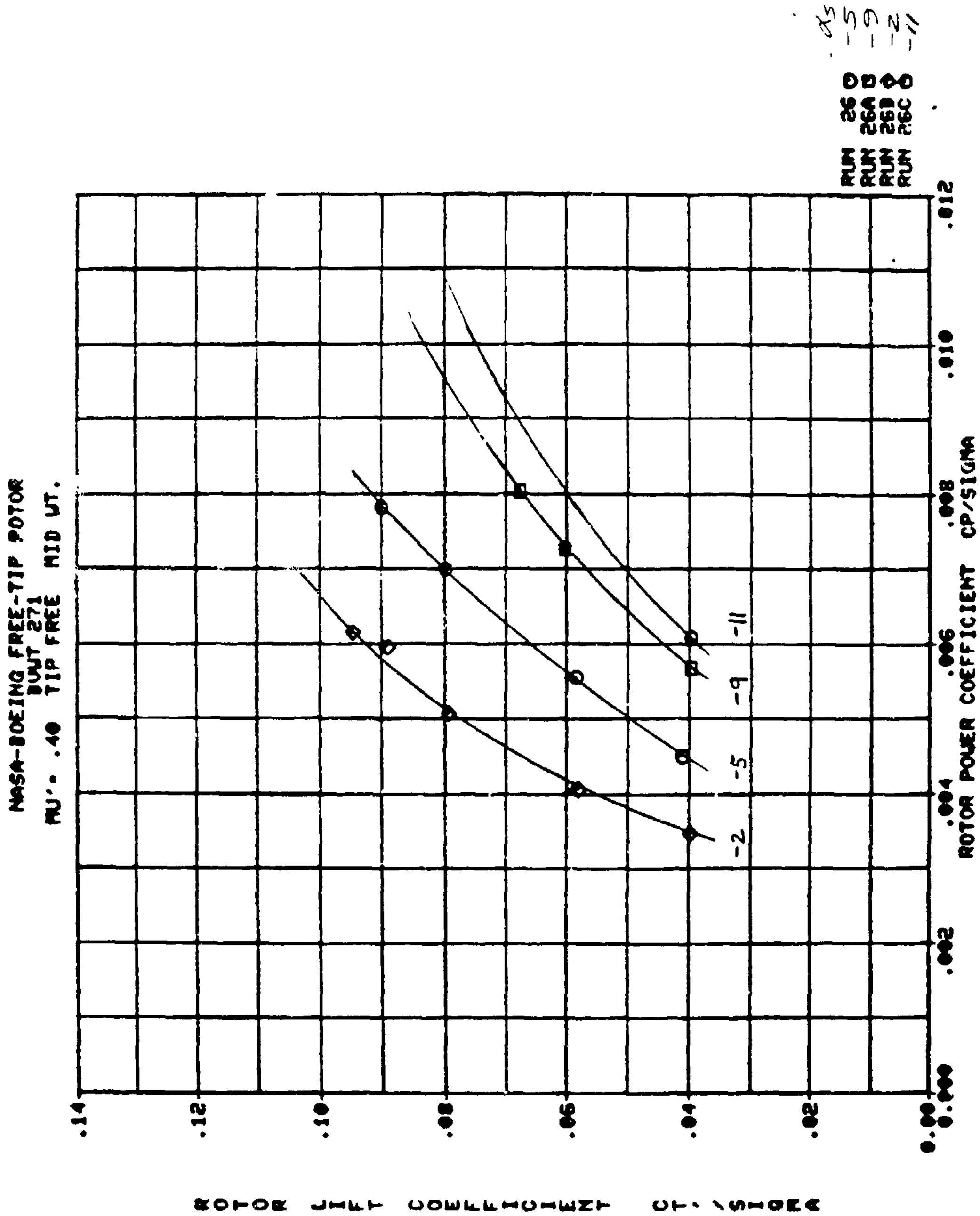

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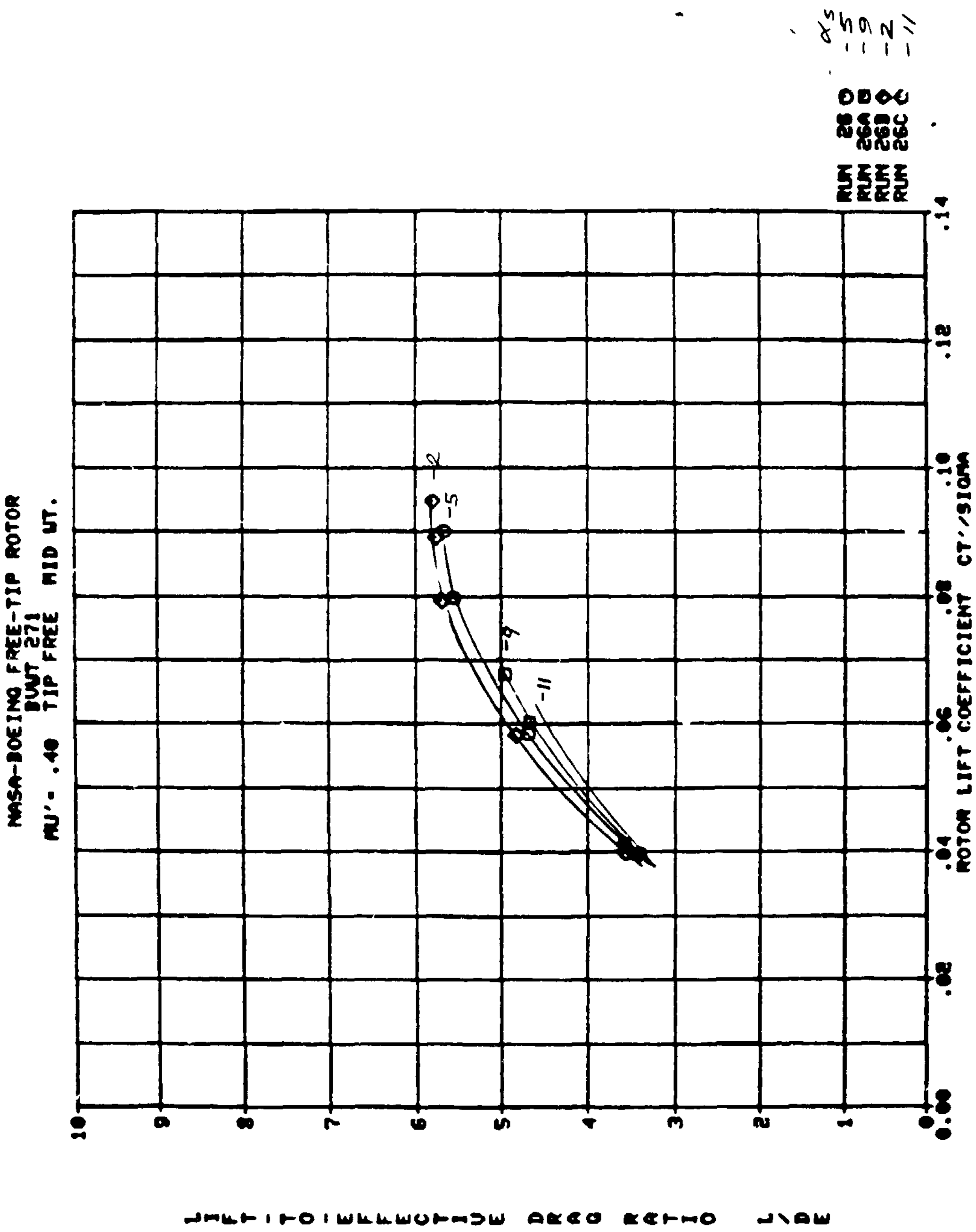

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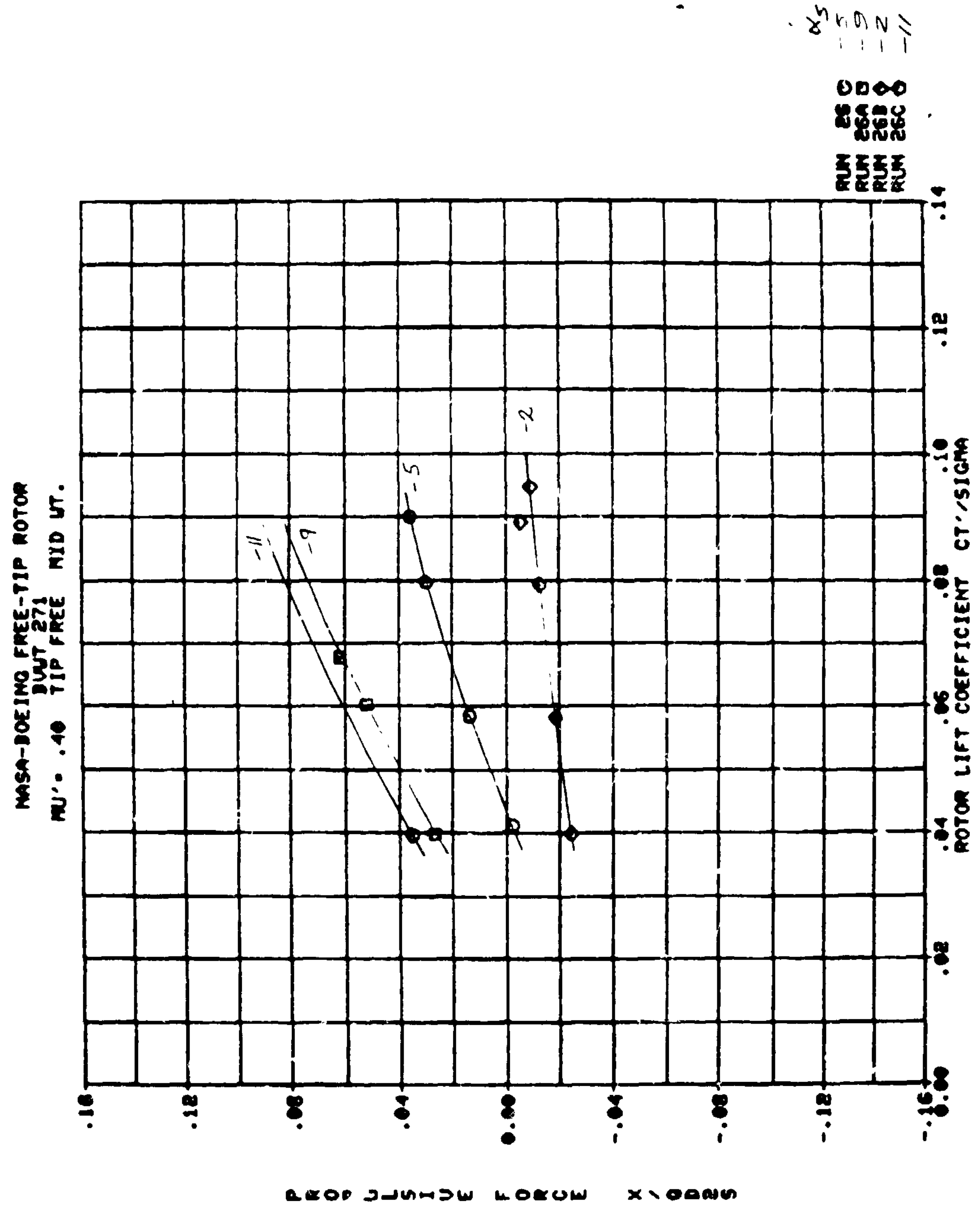

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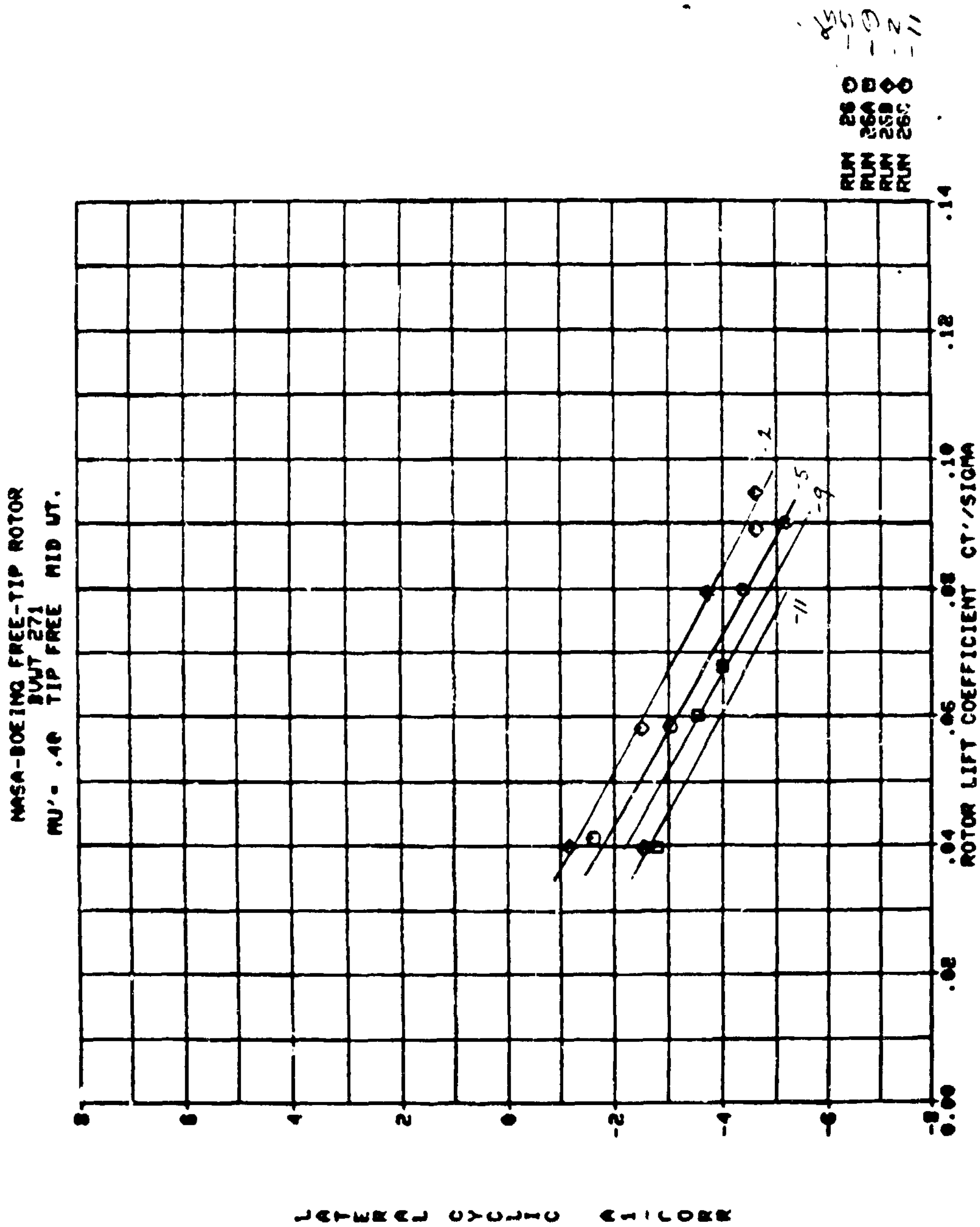

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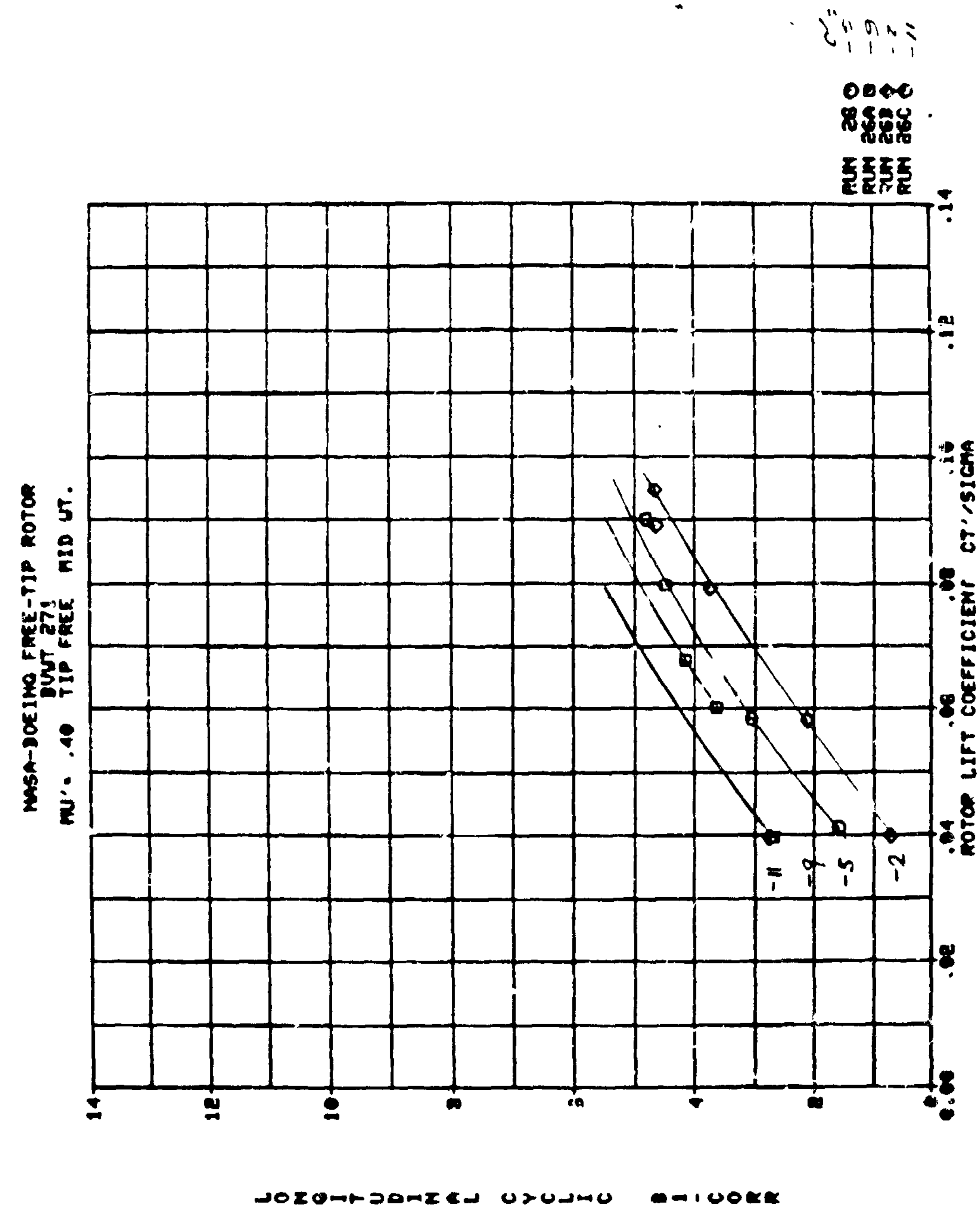
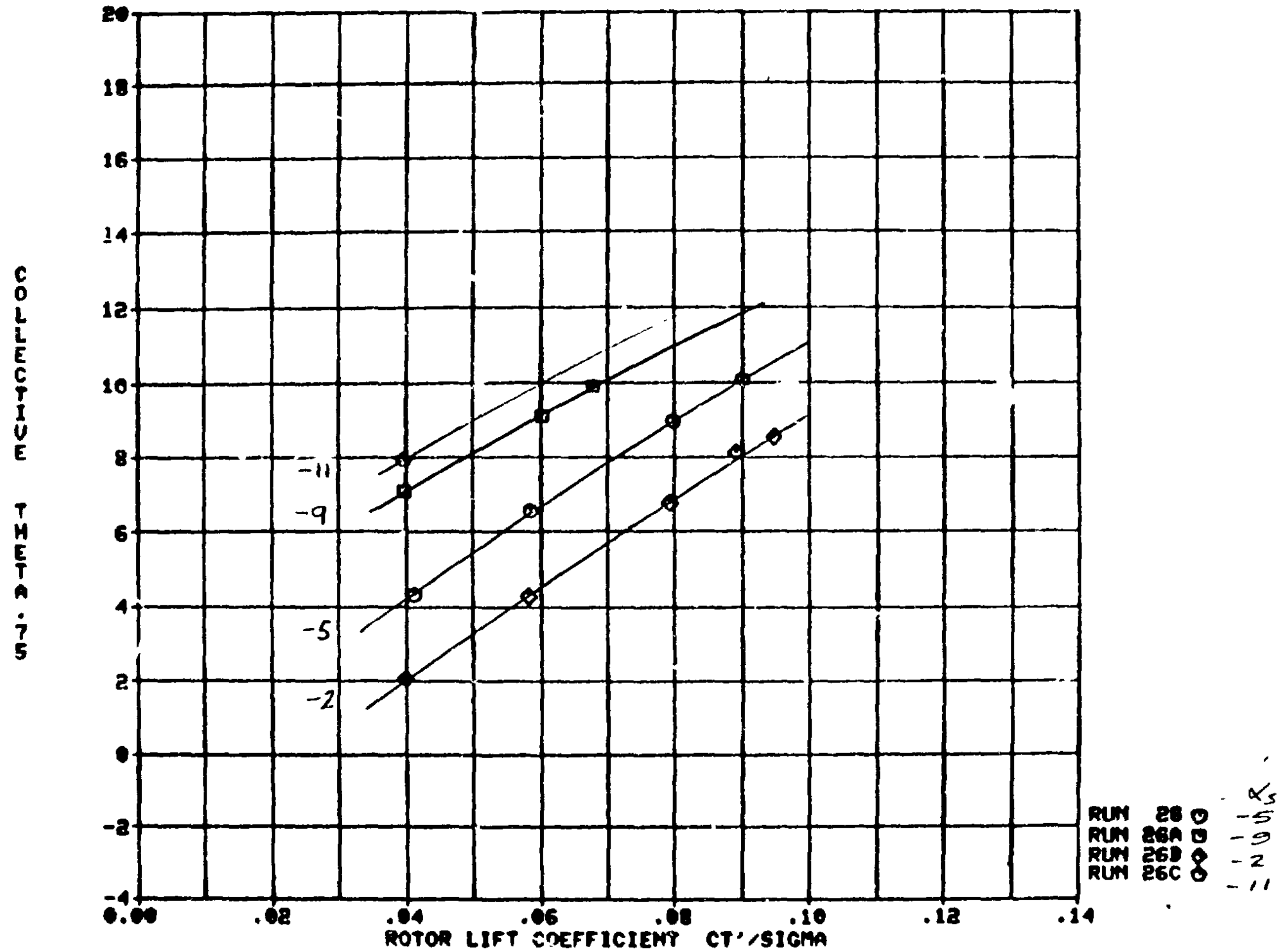


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU' = .40 TIP FREE MID WT.



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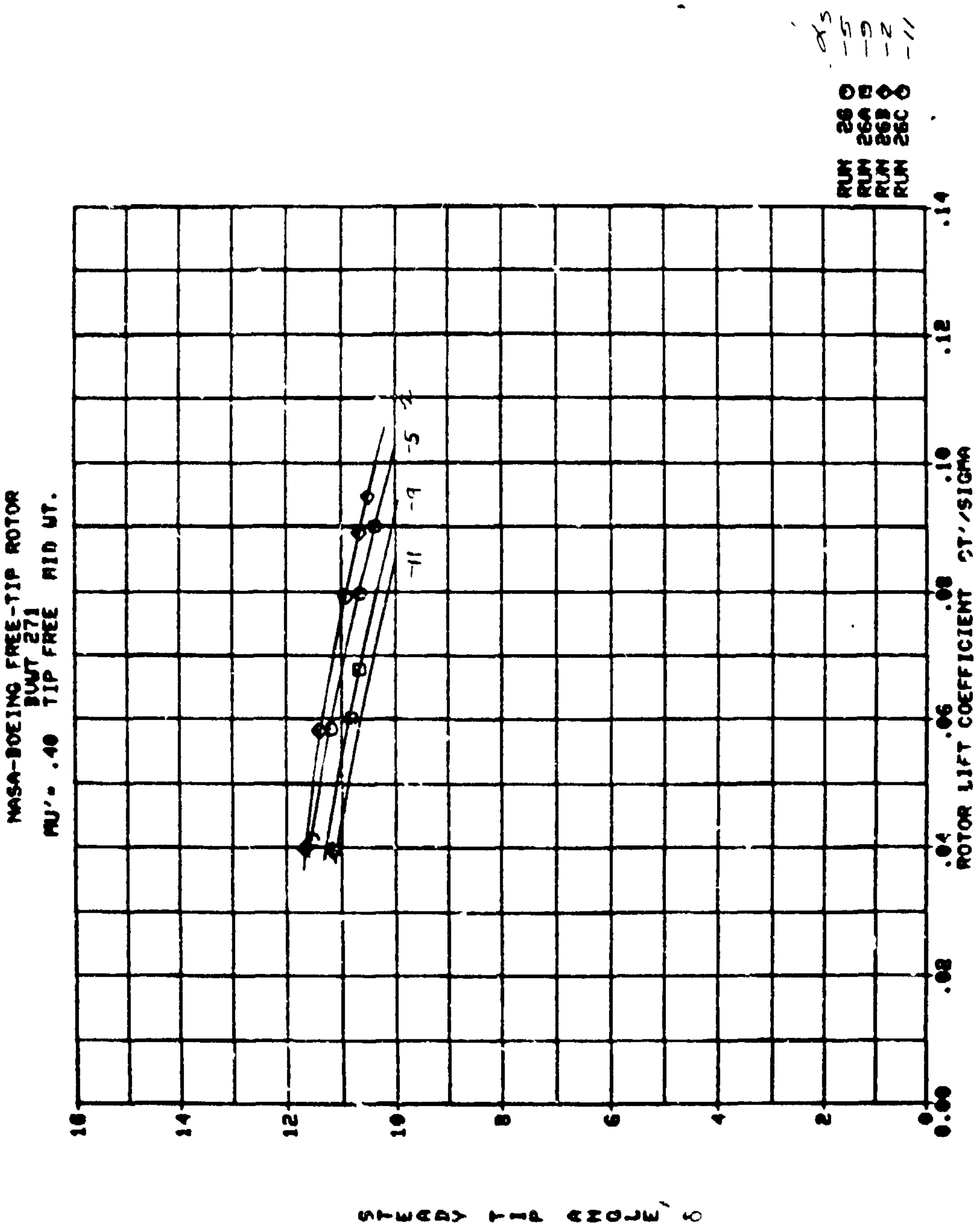
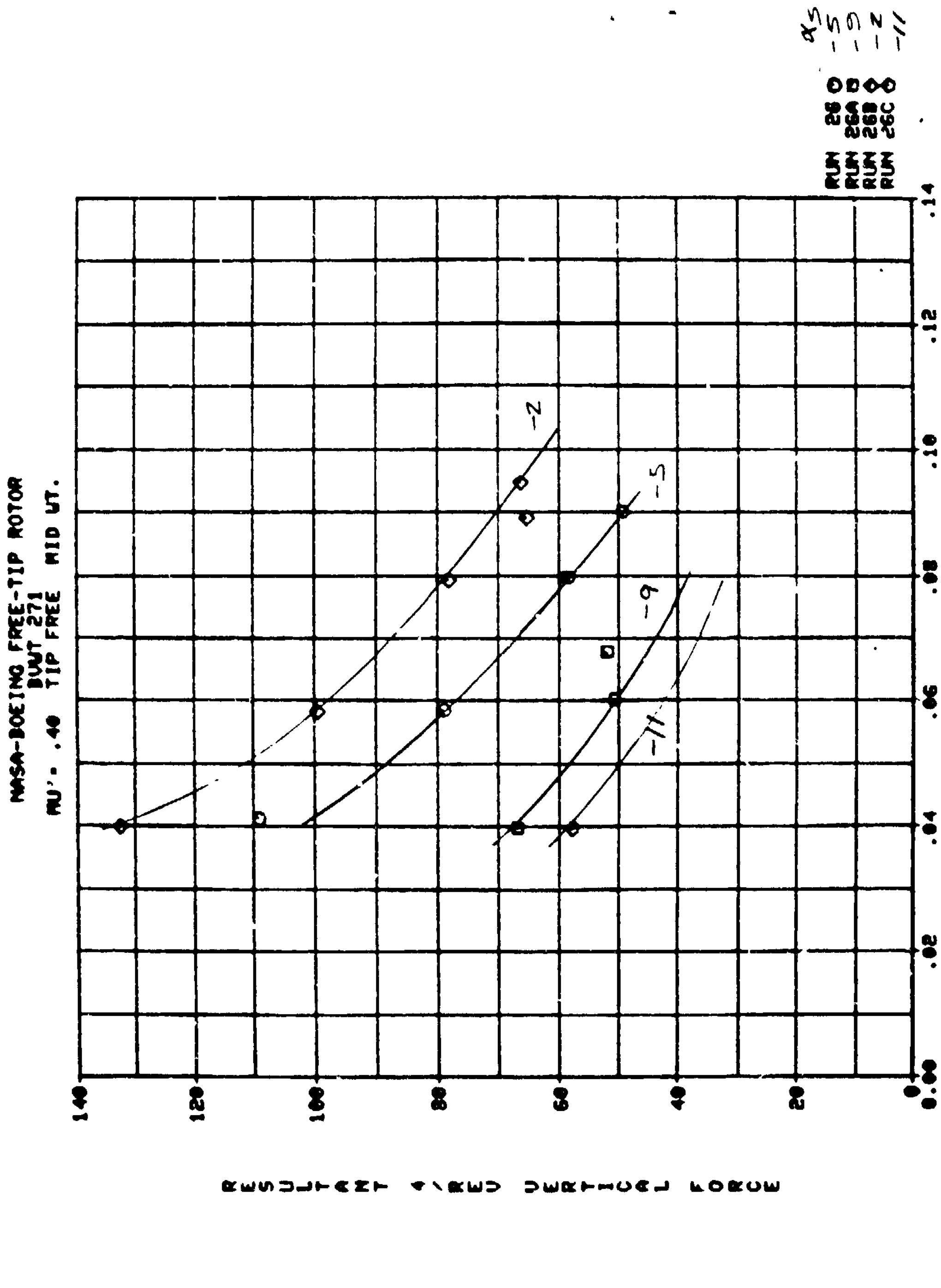
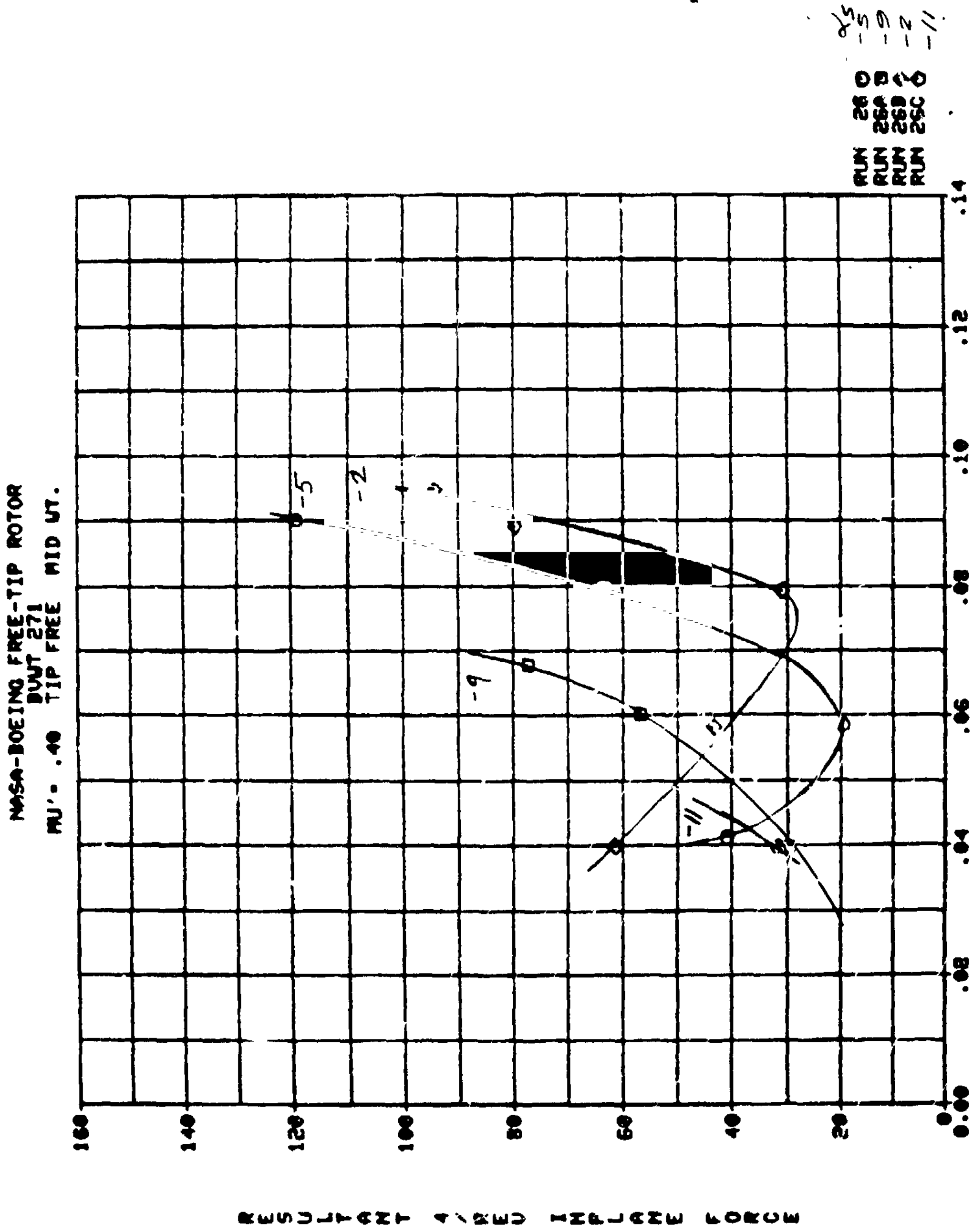
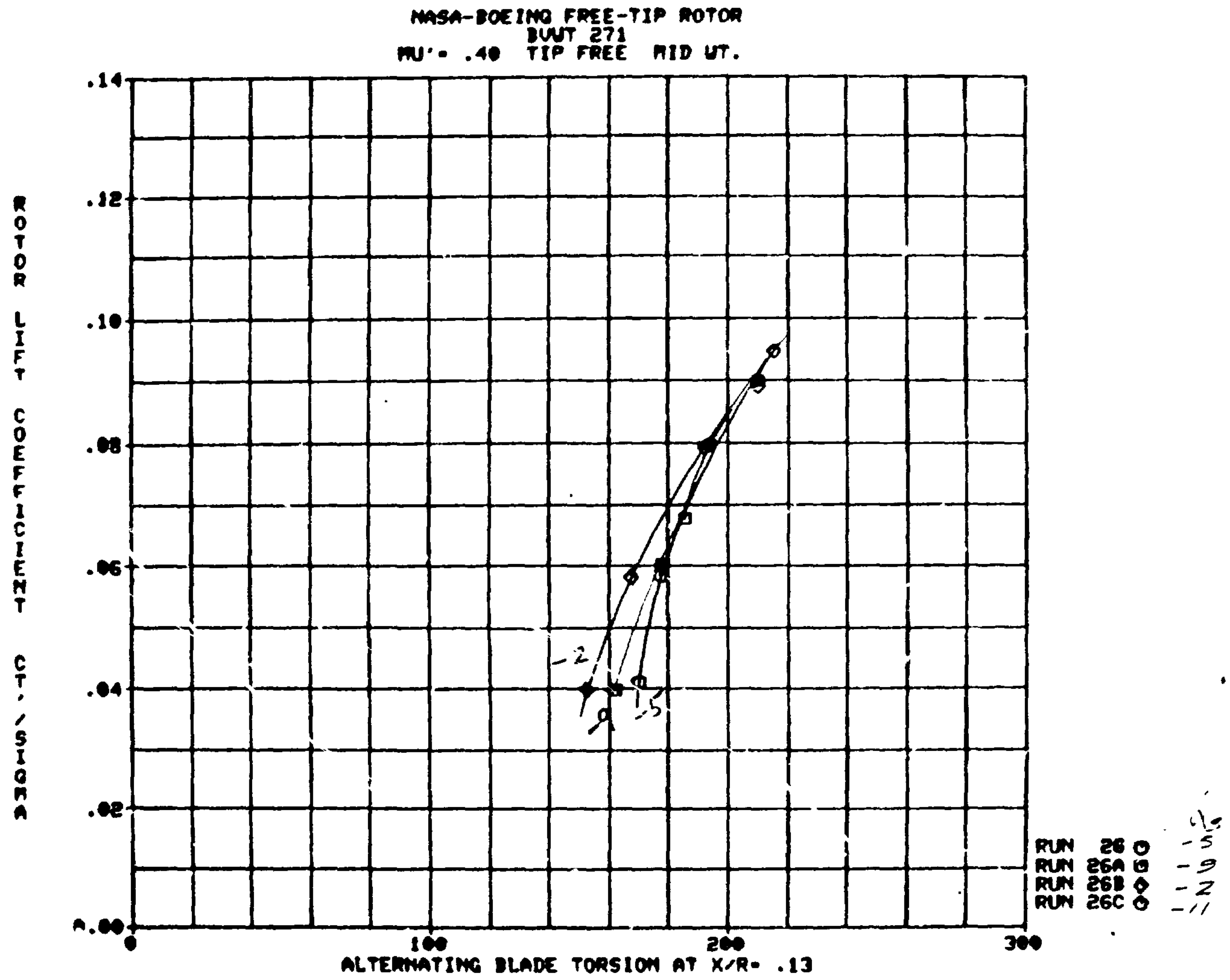



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .40 TIP FREE MID WT.
RUN 26
RUN 26A
RUN 26B
RUN 26C
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
20
40
60
80
100
120
140


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU' = .40 TIP FREE MID WT.
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
20
40
60
80
100
120
140
160
RUN 26
RUN 26A
RUN 26B
RUN 26C
-5
-2
-9
-11


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .40 TIP FREE MID WT.
ROTOR LIFT COEFFICIENT CT'/SIGMA
.14
.12
.10
.08
.06
.04
.02
0.00
0
100
200
300
ALTERNATING BLADE TORSION AT X/R= .13
RUN 26
RUN 26A
RUN 26B
RUN 26C

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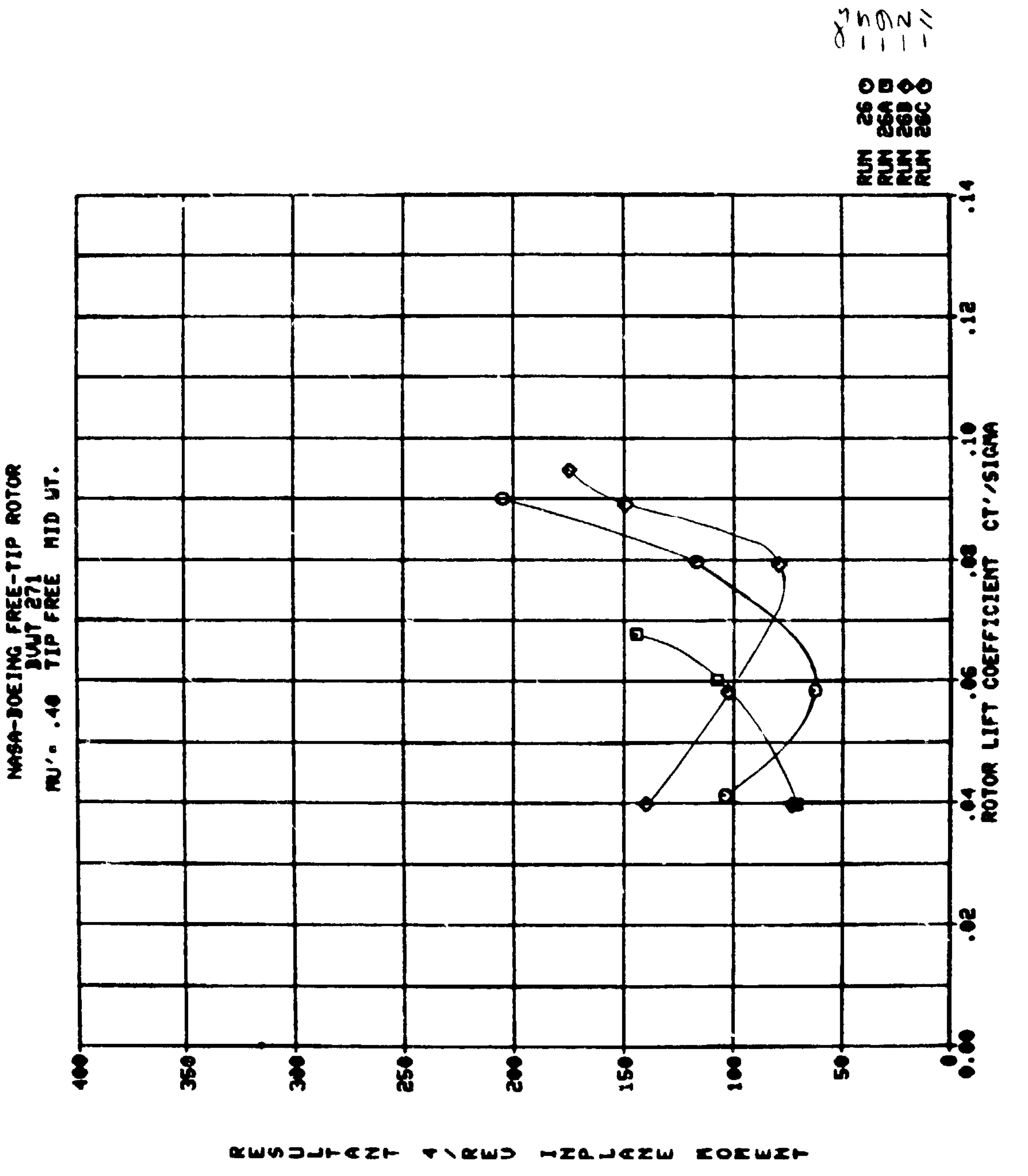

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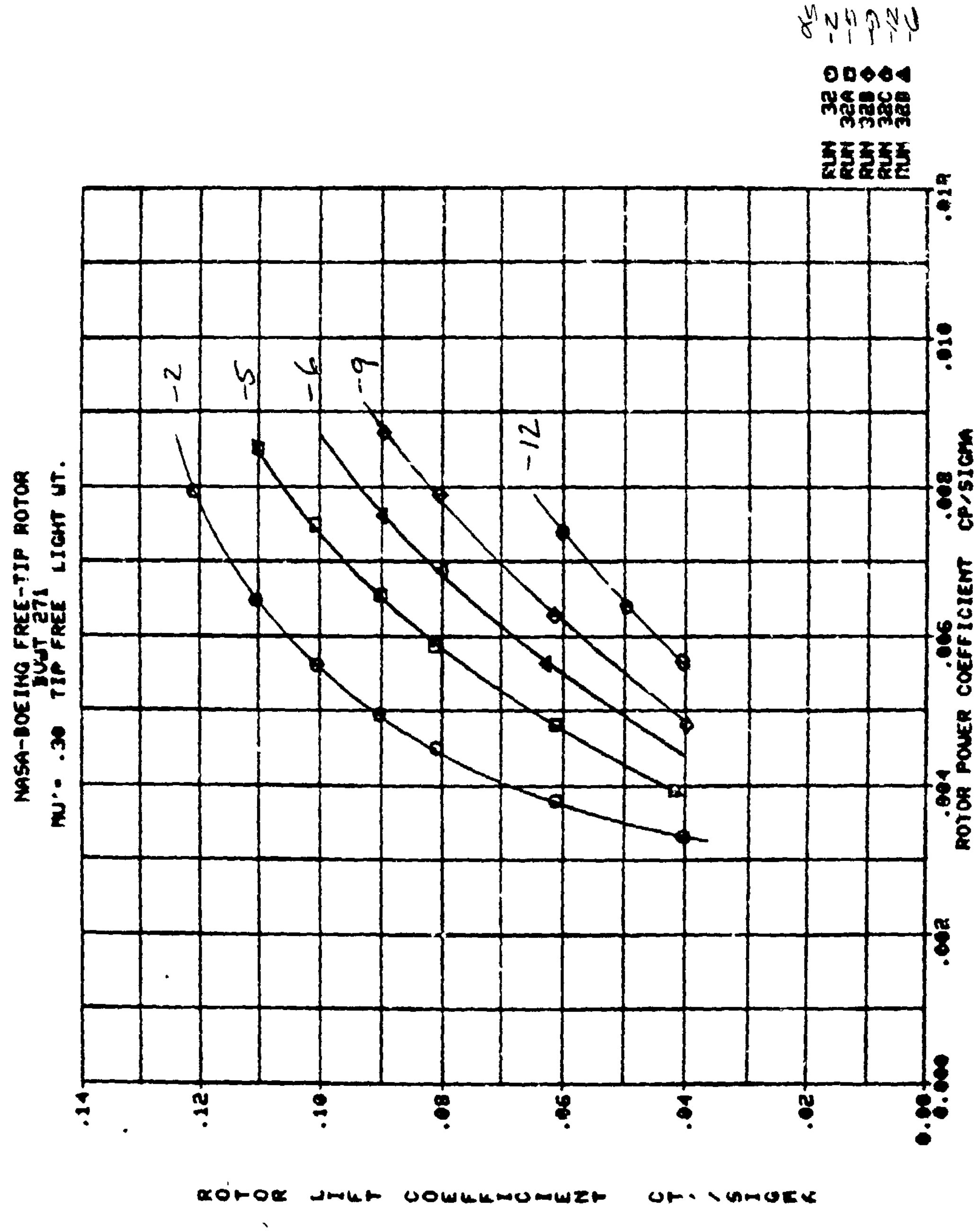

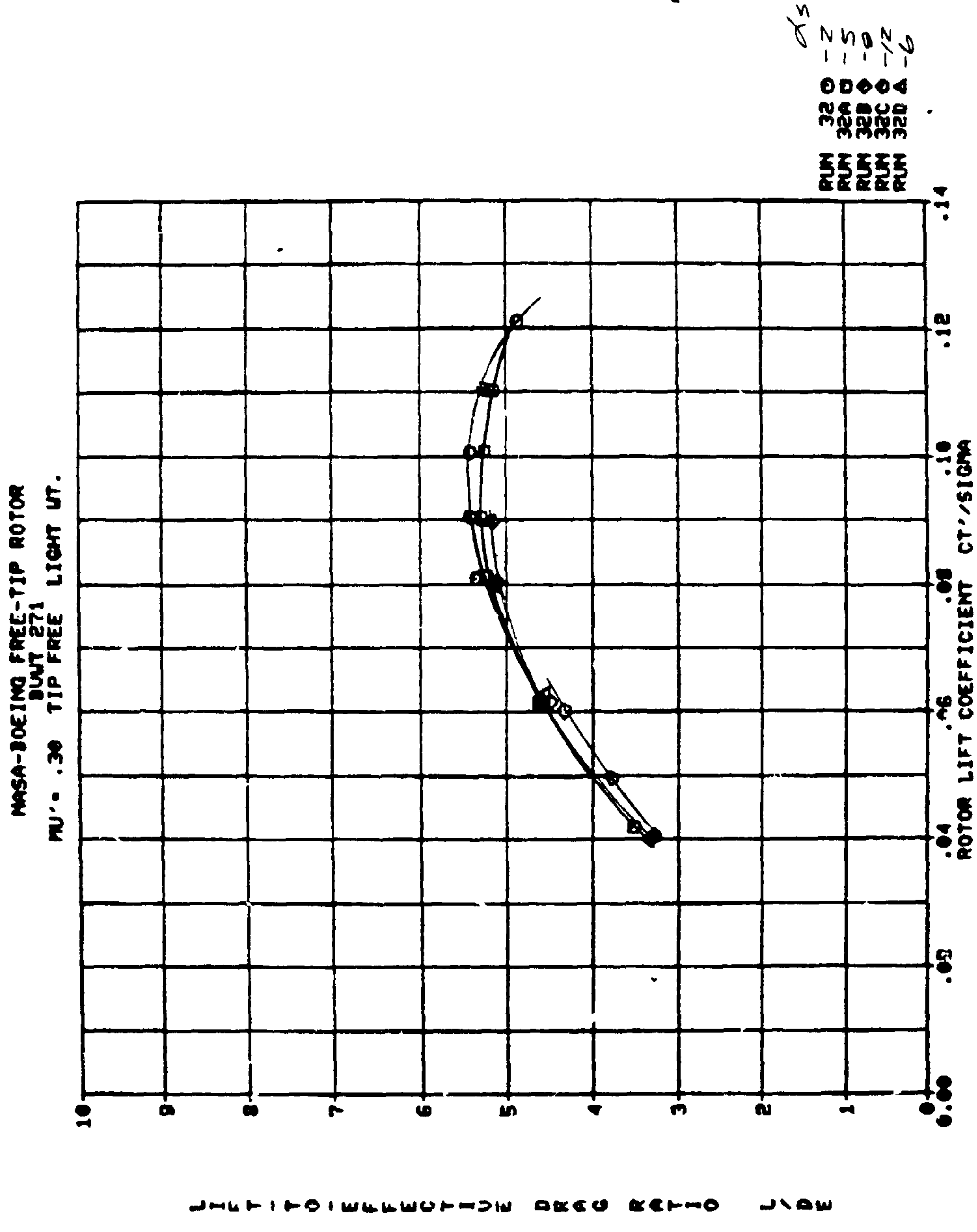
NASA-BOEING FREE-TIP ROTOR
BWT 271
MU' = .30 TIP FREE LIGHT WT.
RUN 32
RUN 32A
RUN 32B
RUN 32C
RUN 32D
ROTOR LIFT COEFFICIENT CT'/SIGMA

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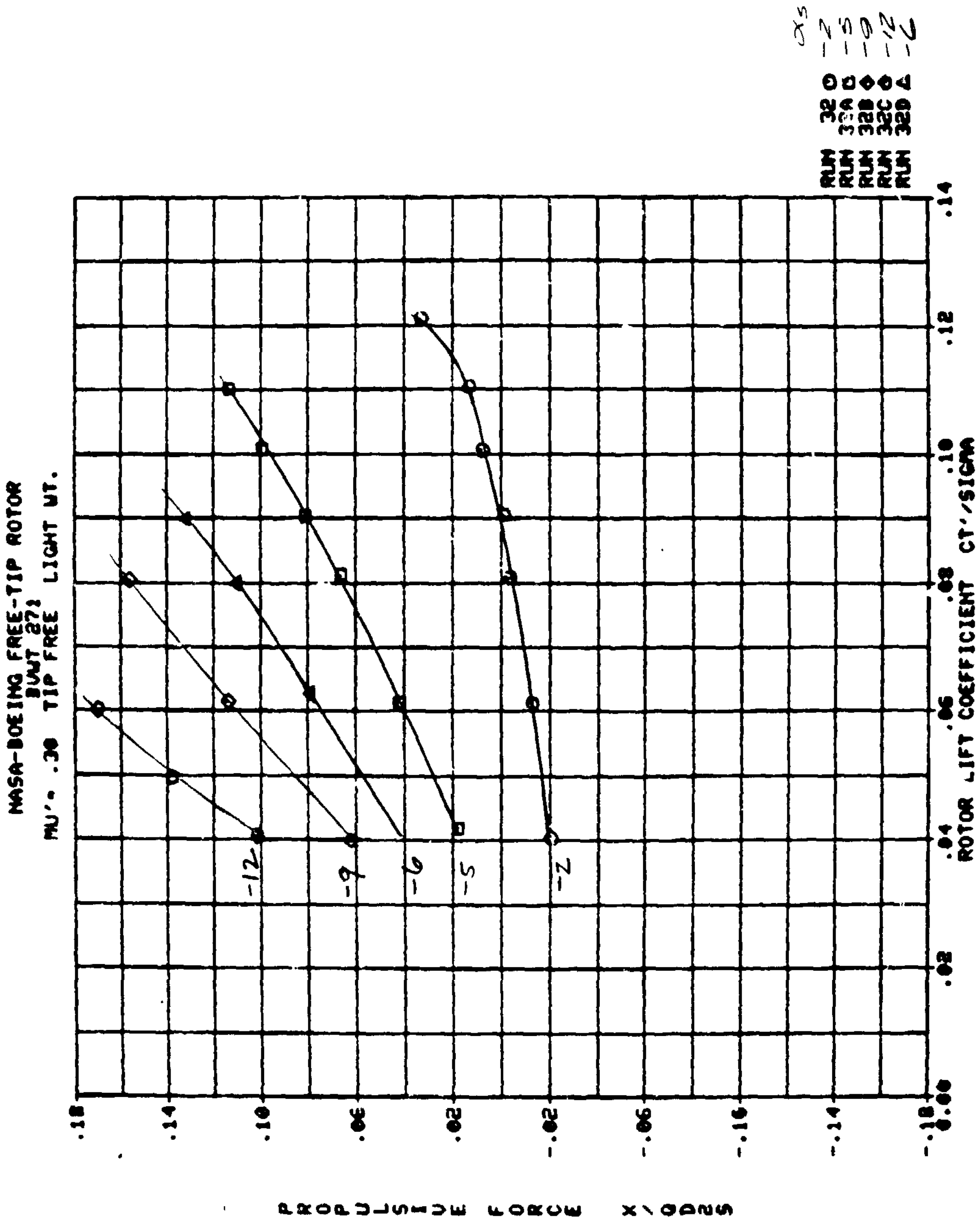

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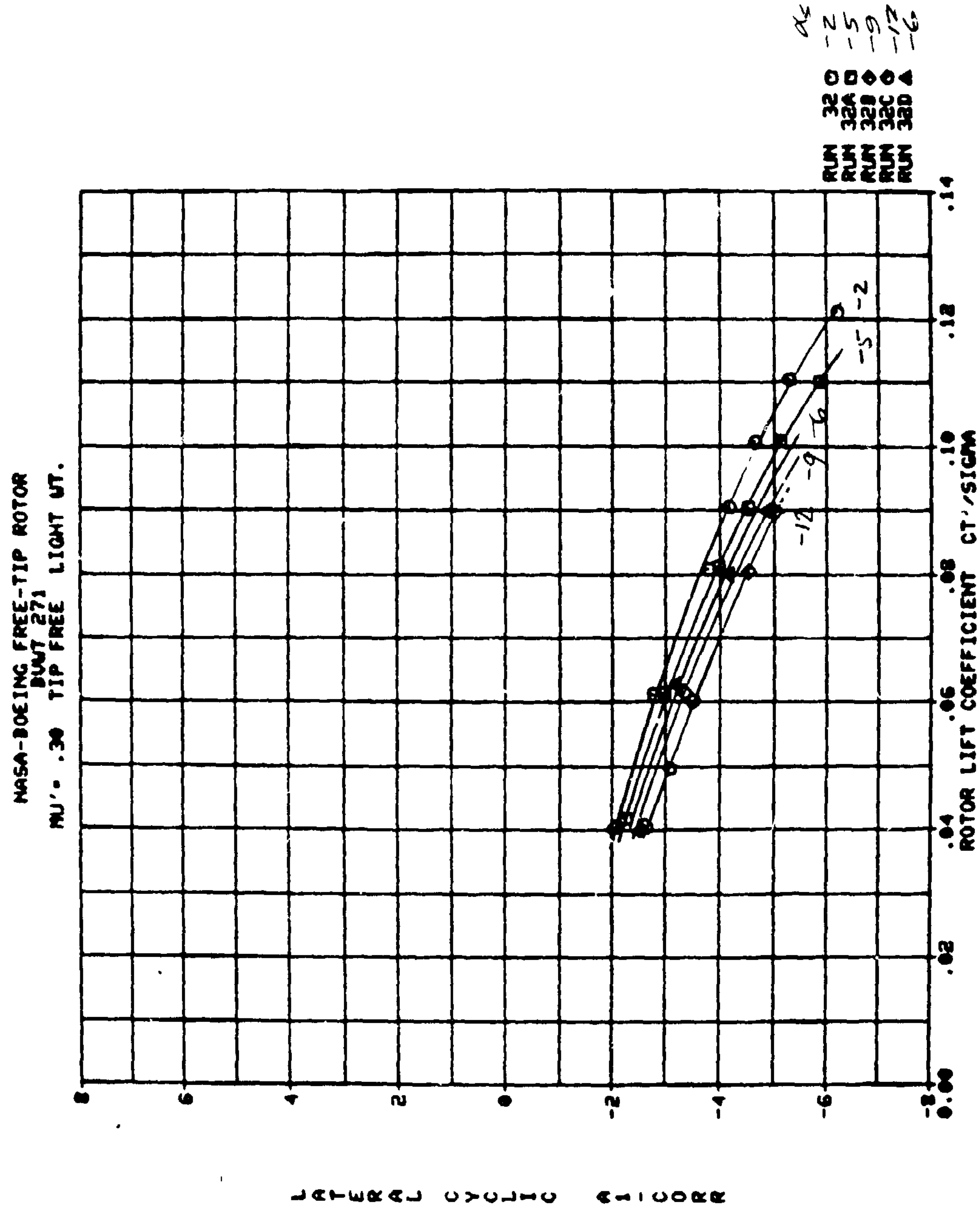

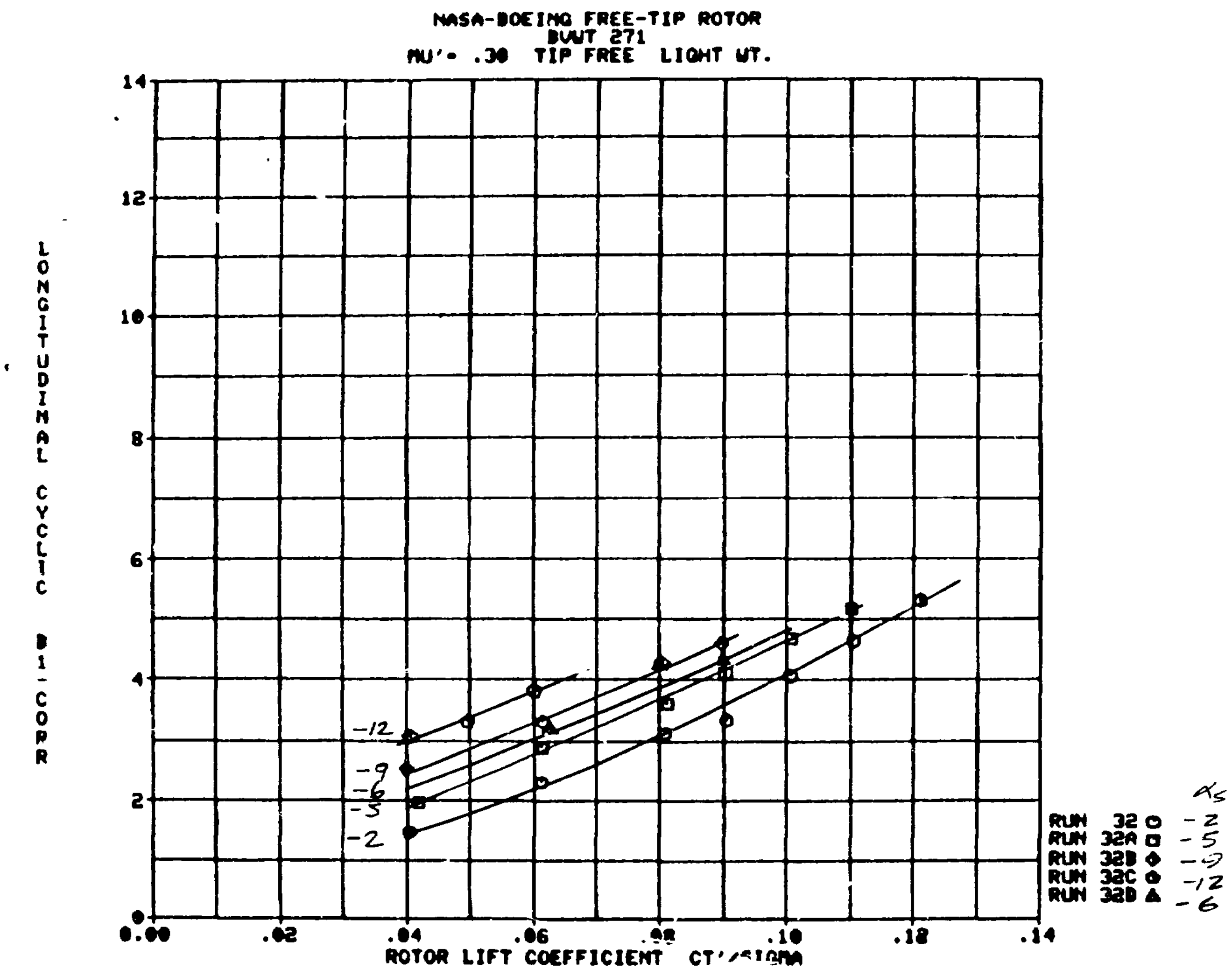
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE LIGHT WT.
LONGITUDINAL CYCLIC B1-CORR
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
2
4
6
8
10
12
14
-12
-9
-6
-5
-2
RUN 32 -2
RUN 32A -5
RUN 32B -9
RUN 32C -12
RUN 32D -6

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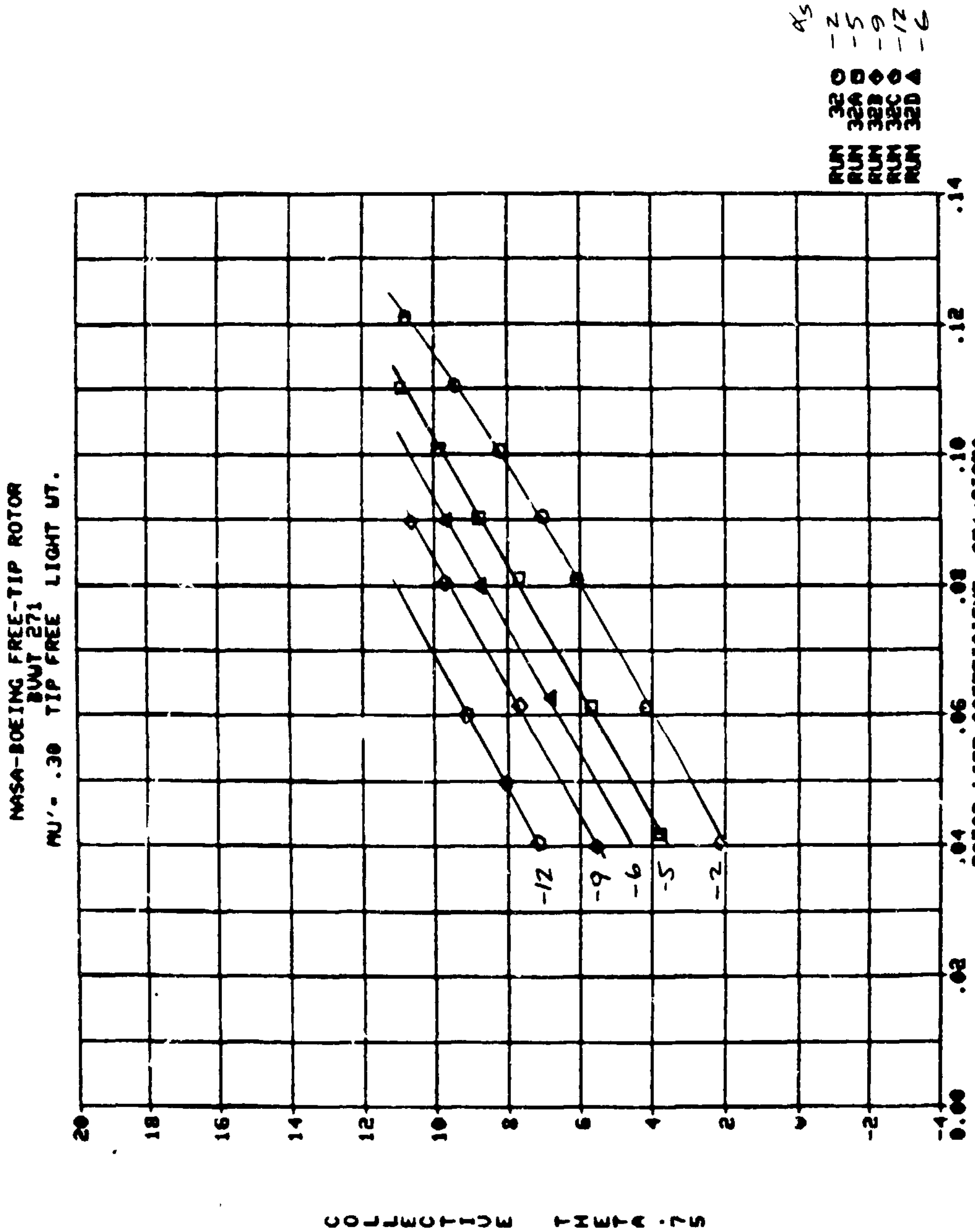

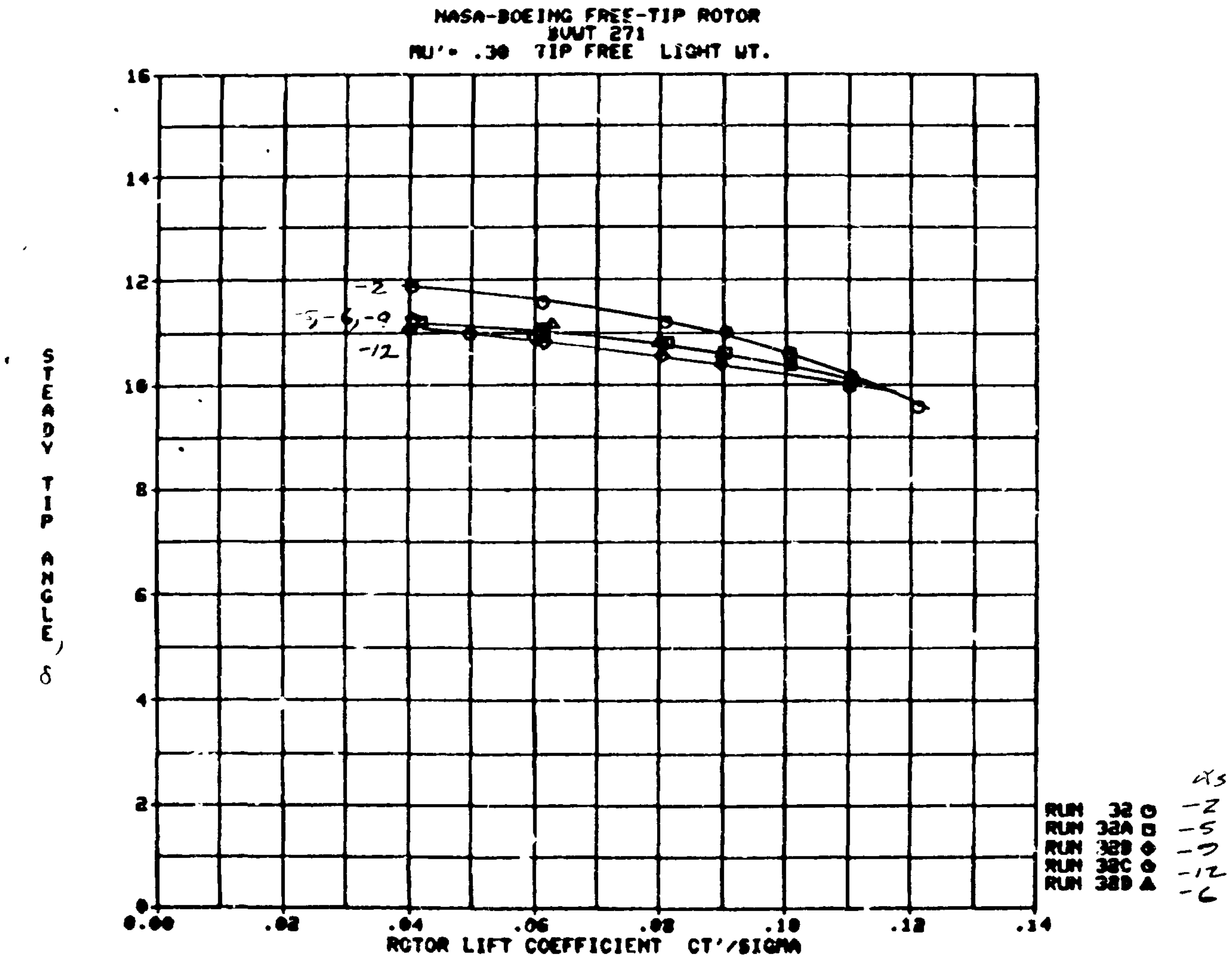
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU' = .30 TIP FREE LIGHT WT.
STEADY TIP ANGLE, δ
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
2
4
6
8
10
12
14
16
-2
-5,-6,-9
-12
α_s
RUN 32 -2
RUN 32A -5
RUN 32B -9
RUN 32C -12
RUN 32D -6

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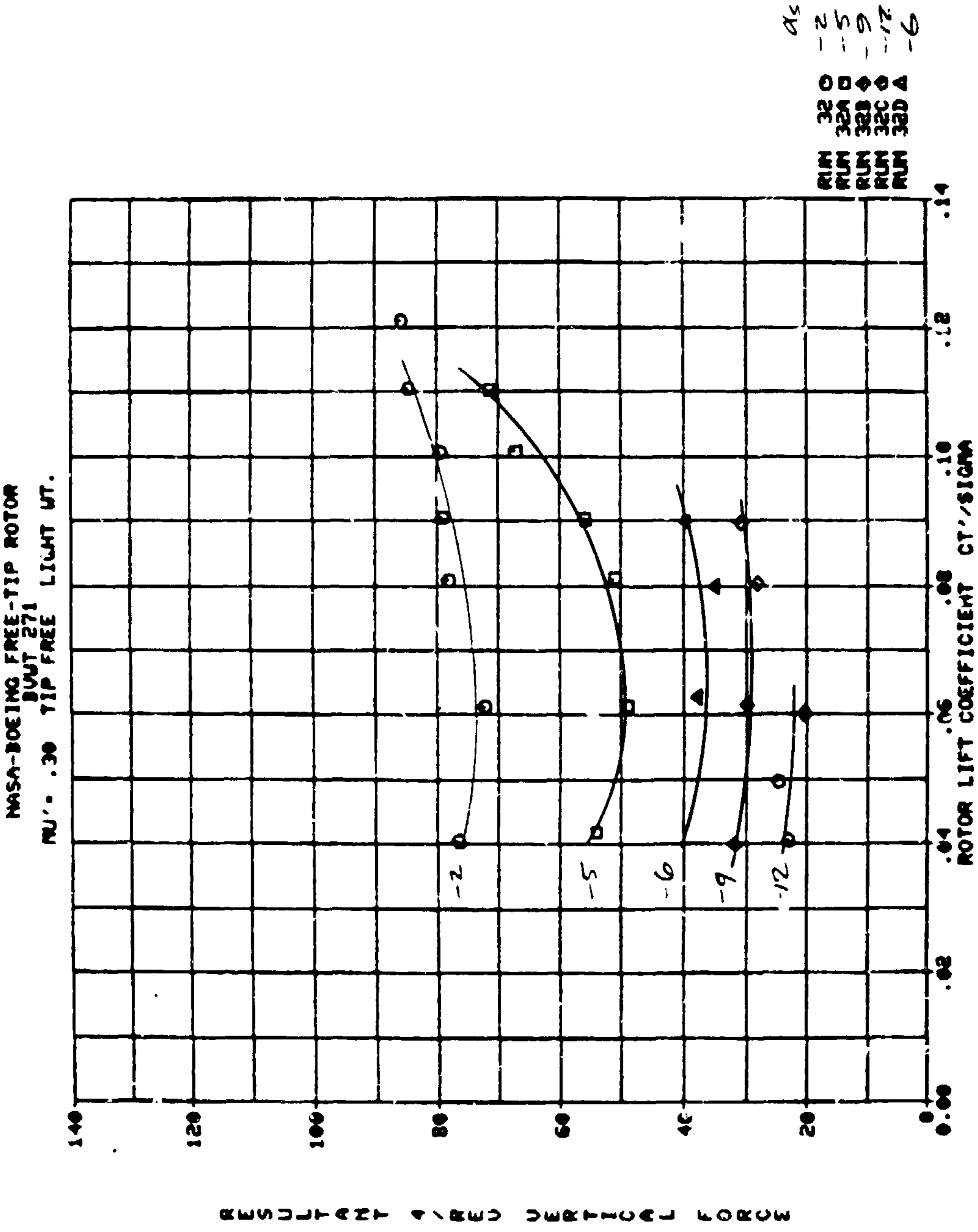

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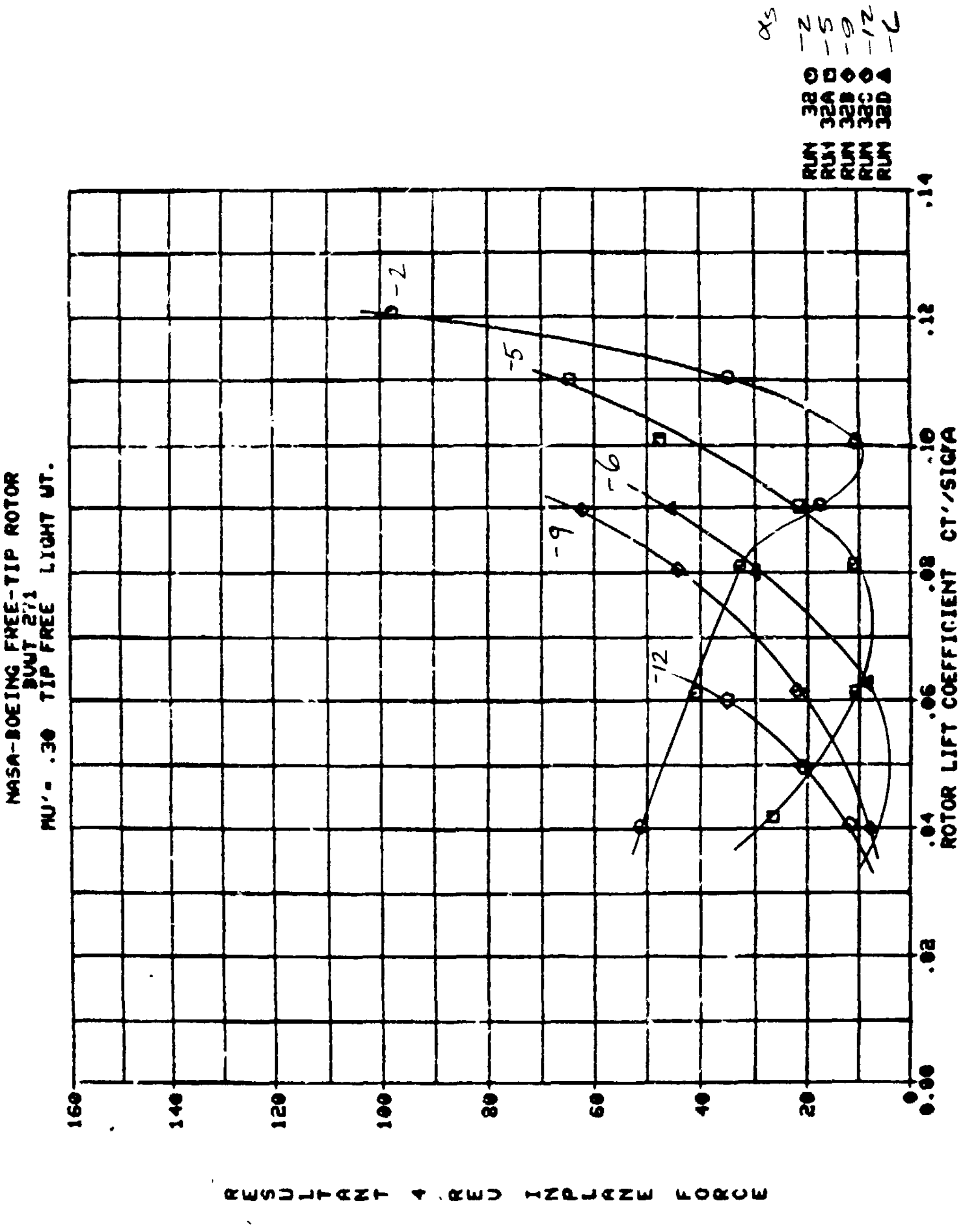

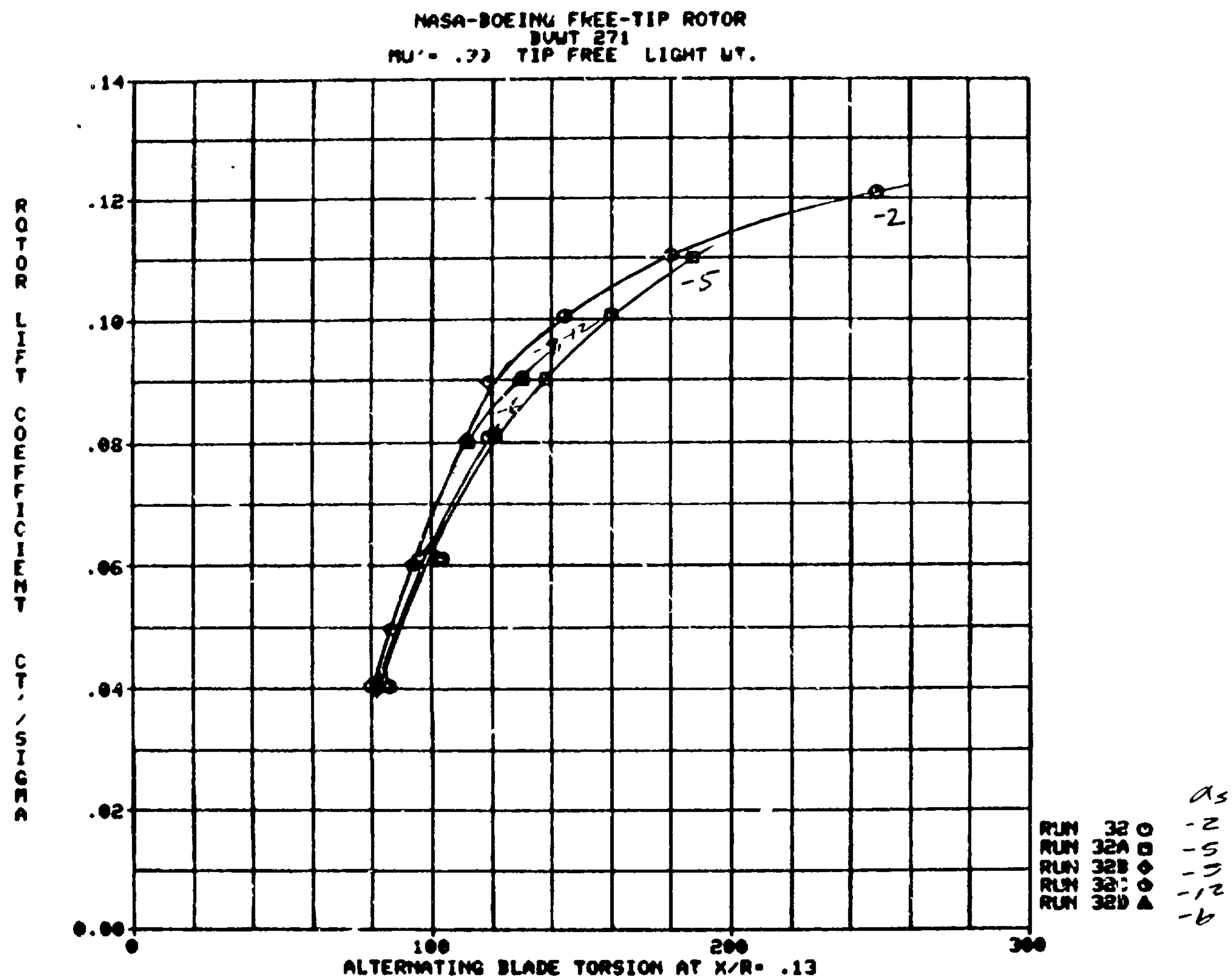
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .33 TIP FREE LIGHT WT.
ROTOR LIFT COEFFICIENT CT'/SIGMA
ALTERNATING BLADE TORSION AT X/R= .13
.14
.12
.10
.08
.06
.04
.02
0.00
0
100
200
300
-2
-5
-12
-6
αs
RUN 32 -2
RUN 32A -5
RUN 32B -5
RUN 32C -12
RUN 32D -6

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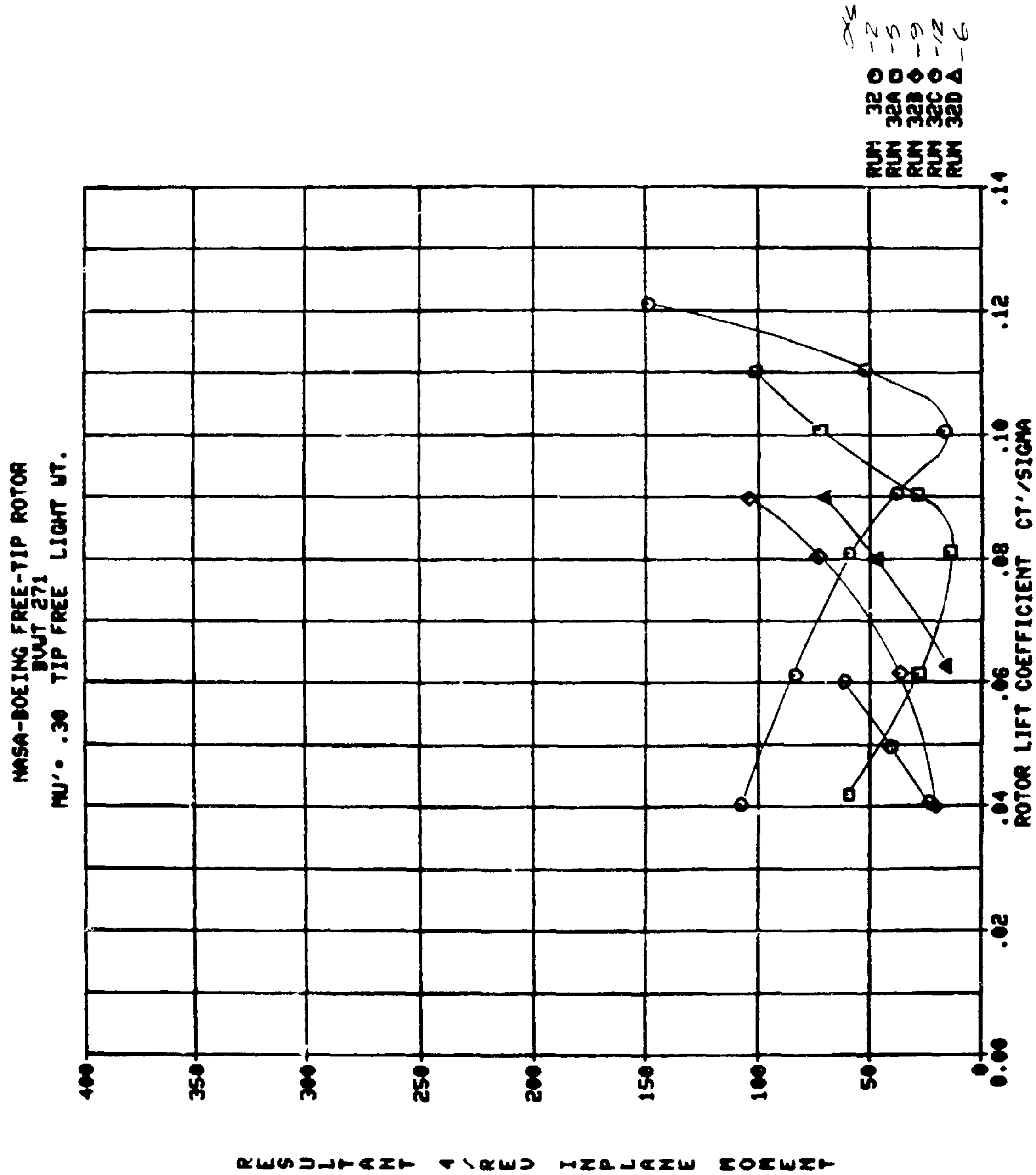

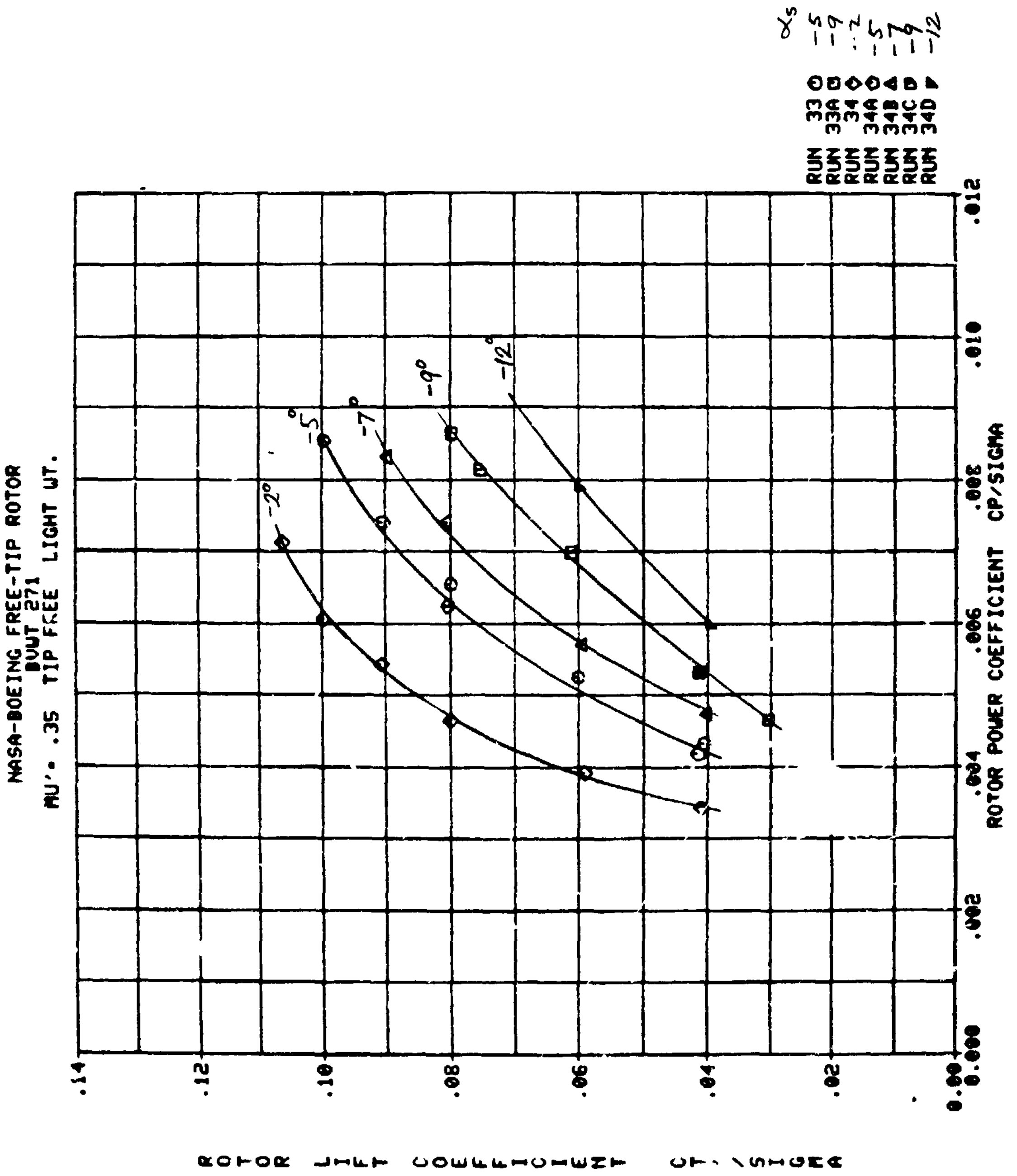
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FREE LIGHT WT.
RUN 33 O -5
RUN 33A □ -9
RUN 34 ◇ -2
RUN 34A ○ -5
RUN 34B △ -7
RUN 34C ◻ -9
RUN 34D ▼ -12
α_s
-2°
-5°
-7°
-9°
-12°
ROTOR POWER COEFFICIENT CP/SIGMA
.000
.002
.004
.006
.008
.010
.012
0.00
.02
.04
.06
.08
.10
.12
.14

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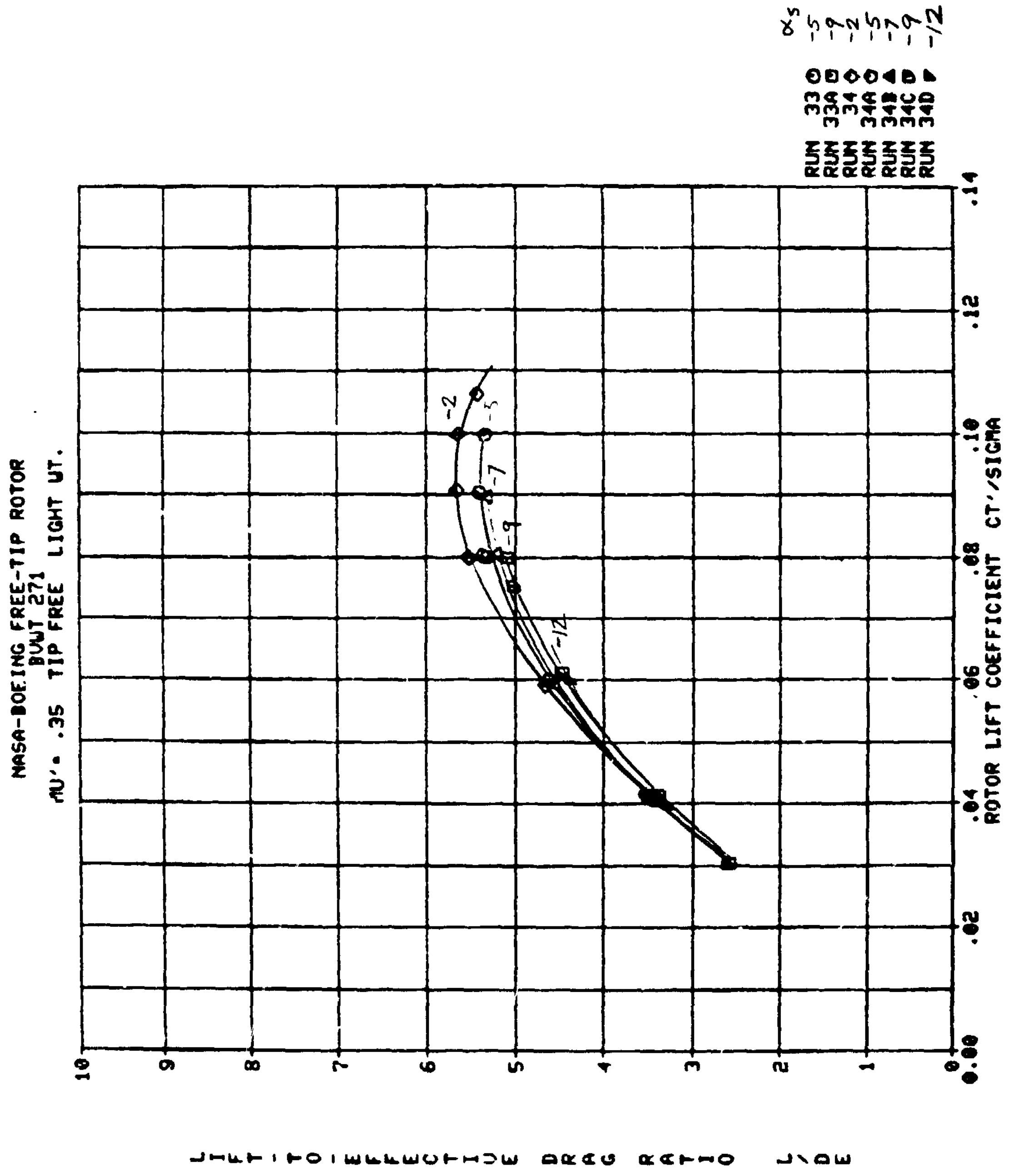

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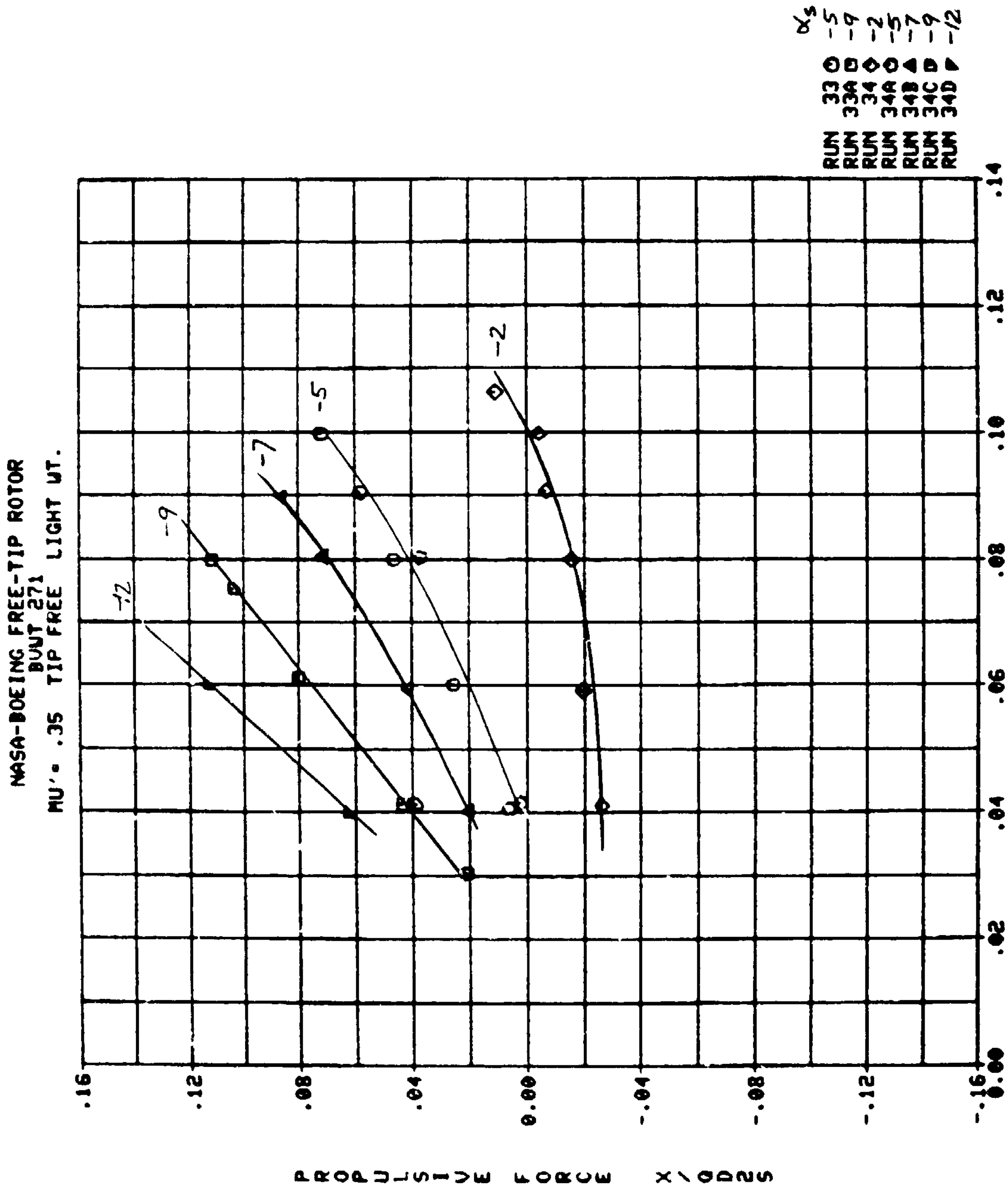
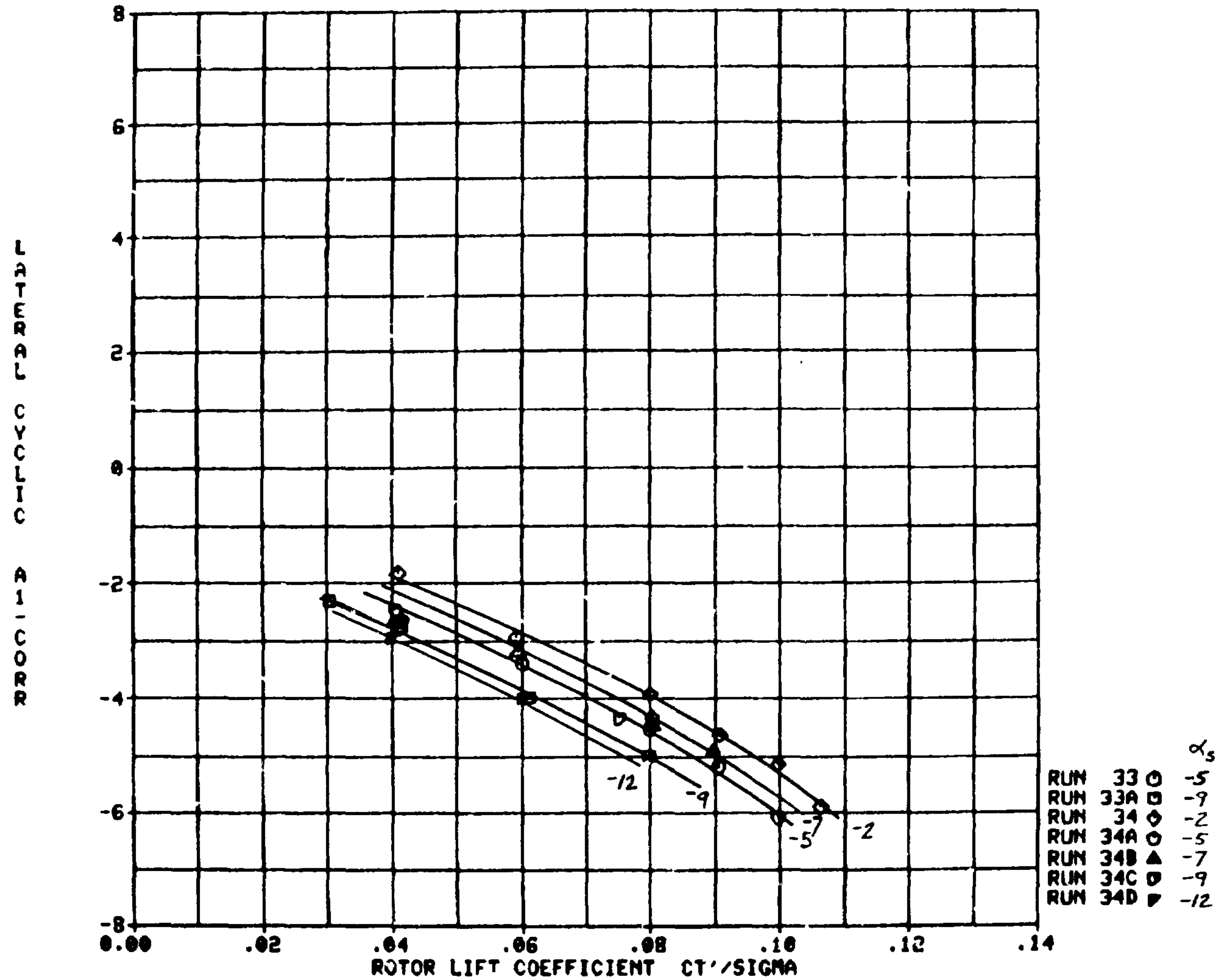


NASA-BOEING FREE-TIP ROTOR
BVW. 271
MU'= .35 TIP FREE LIGHT WT.



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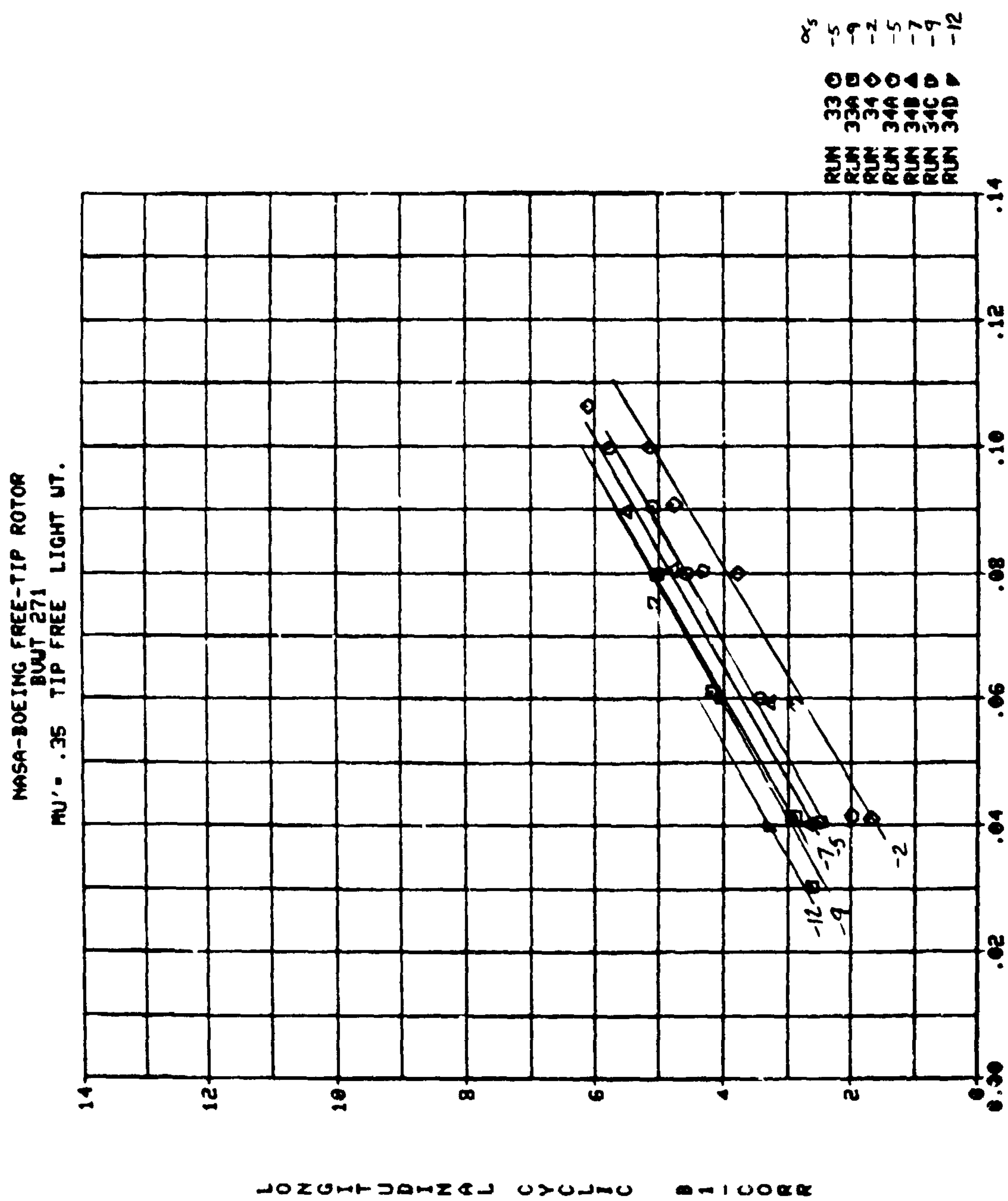

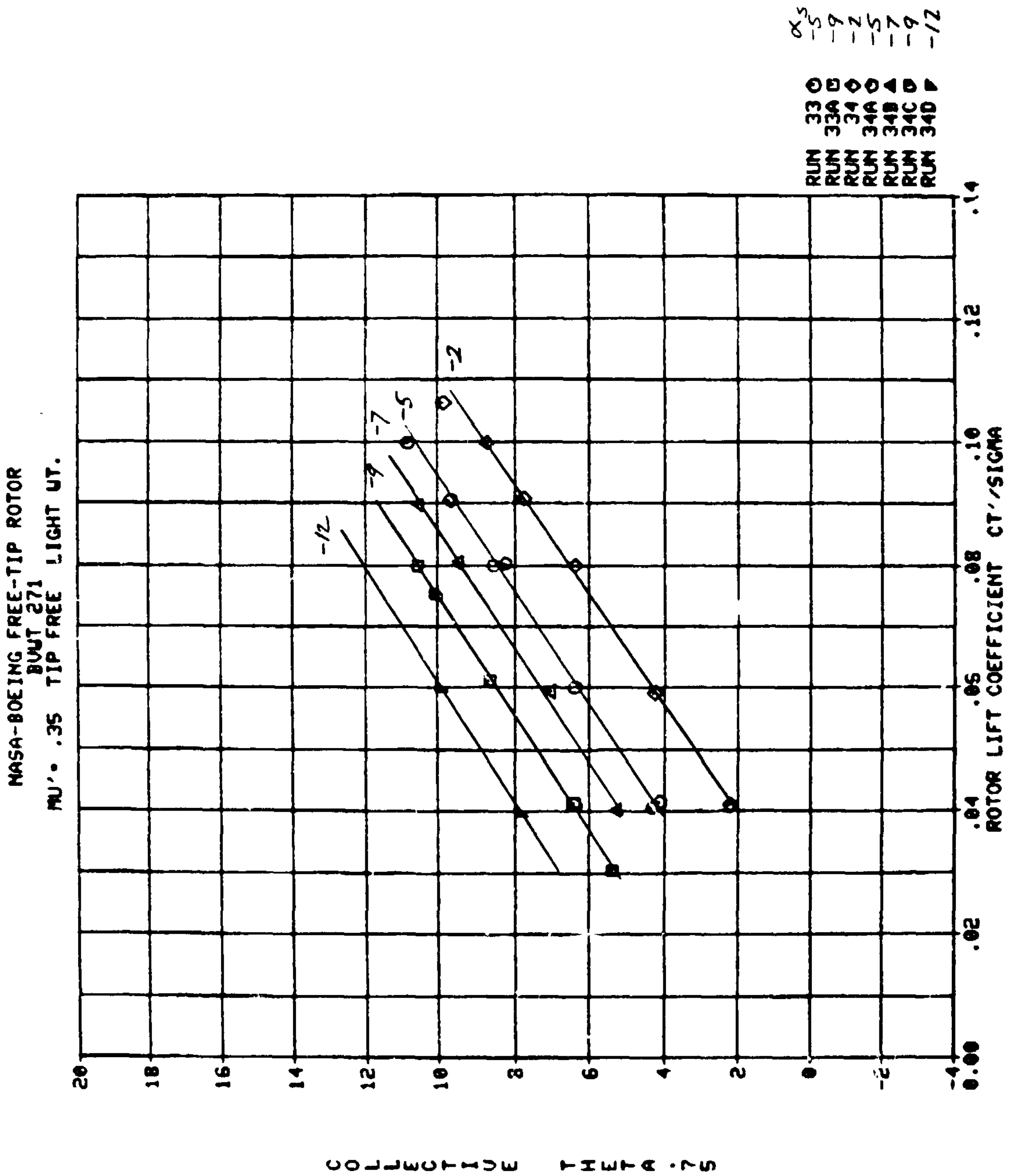
NASA-BOEING FREE-TIP ROTOR
BUWT 271
MU'= .35 TIP FREE LIGHT WT.
RUN 33 -5
RUN 33A -9
RUN 34 -2
RUN 34A -5
RUN 34B -7
RUN 34C -9
RUN 34D -12
α_s
ROTOR LIFT COEFFICIENT CT'/SIGMA
COLLECTIVE THETA.75
0.00
.02
.04
.06
.08
.10
.12
.14
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-2
-5
-7
-9
-12

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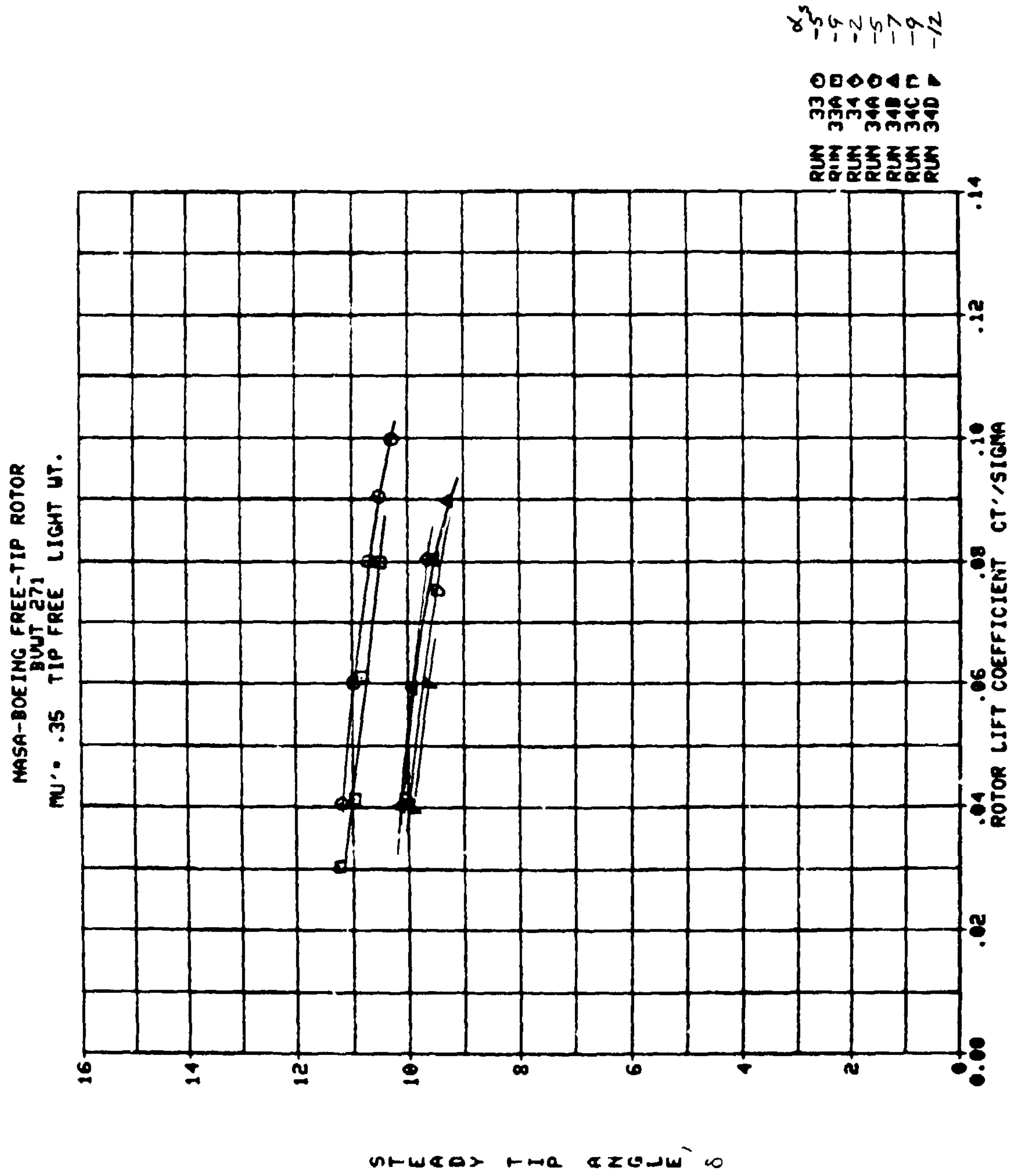

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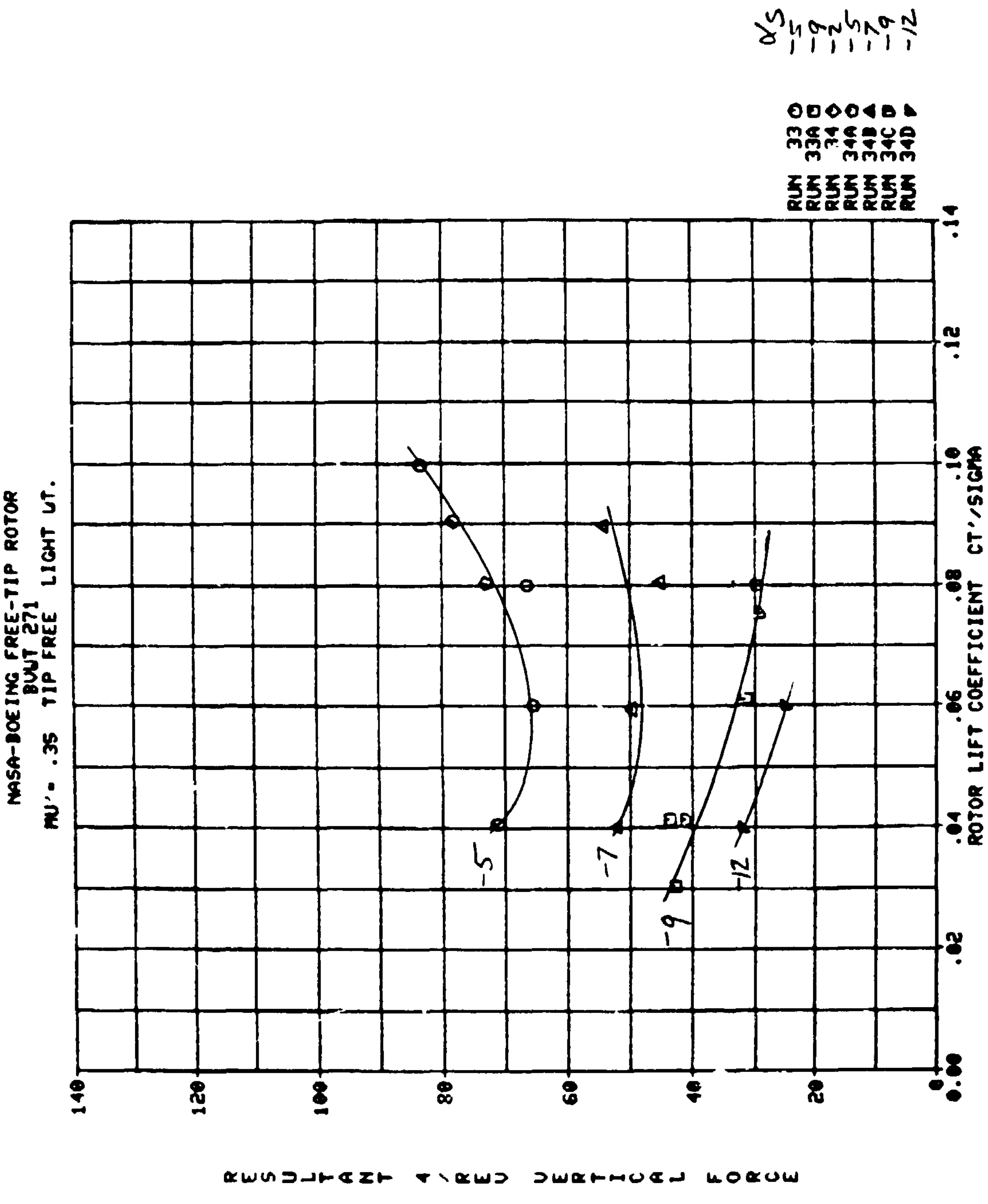

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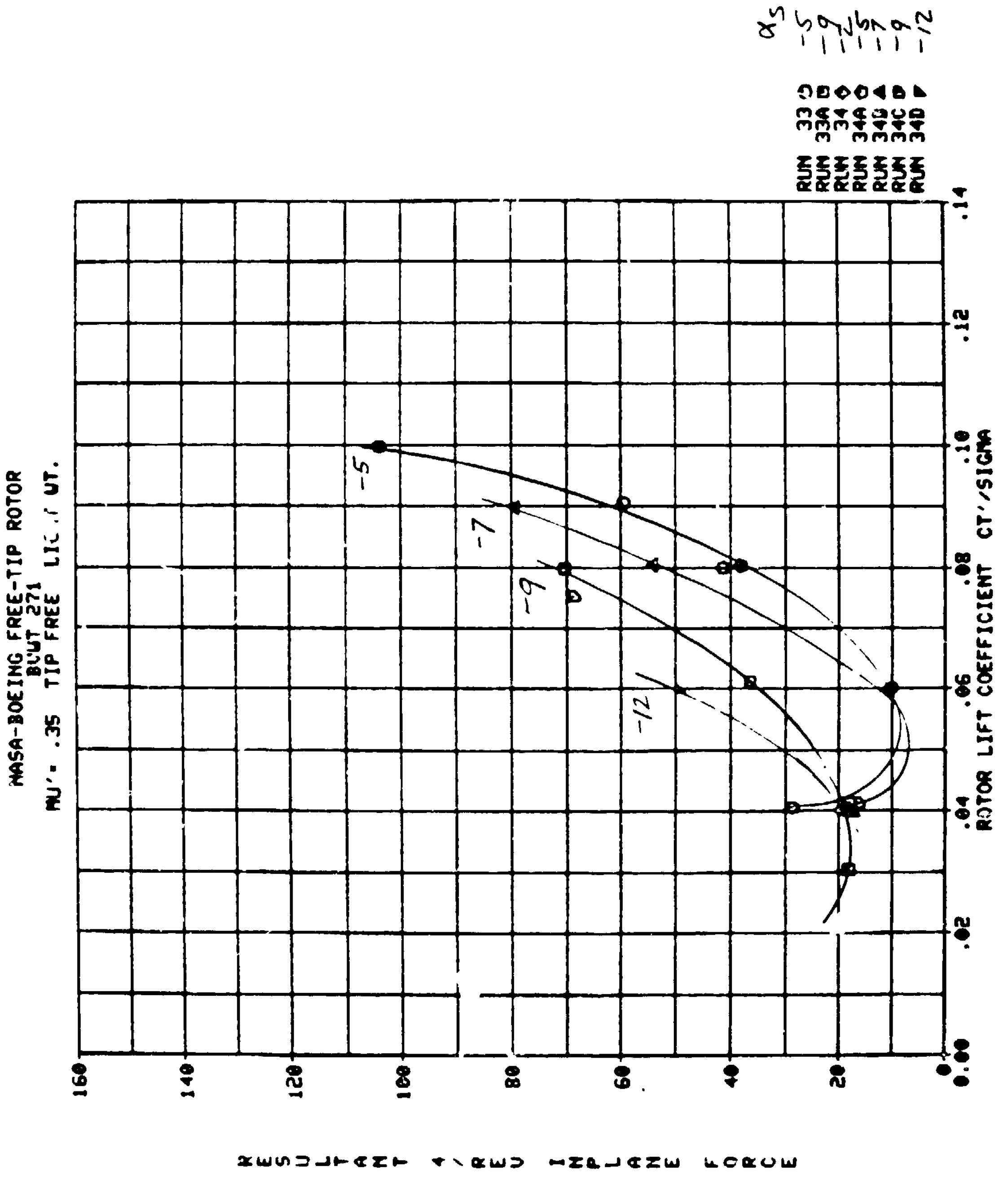

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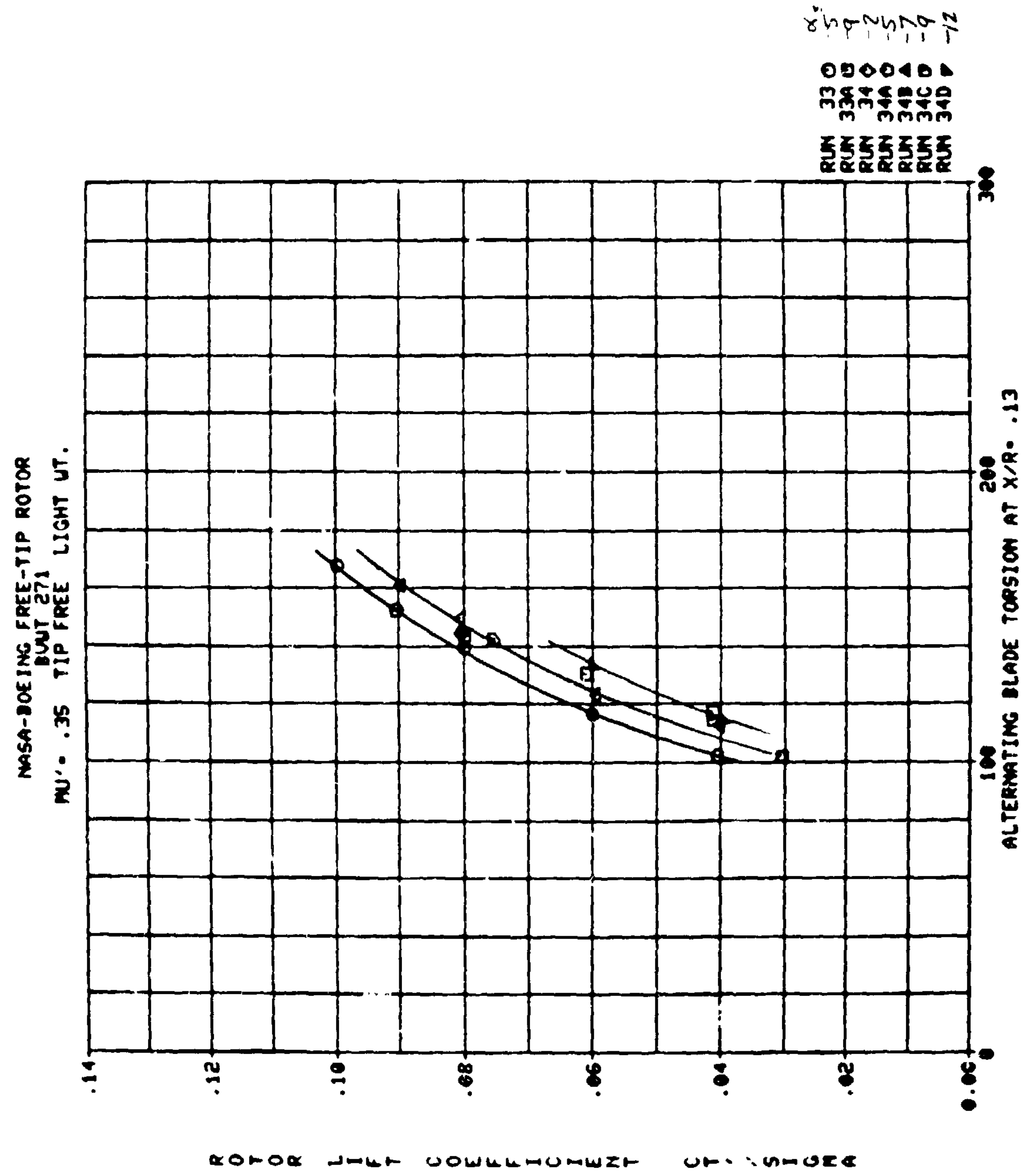

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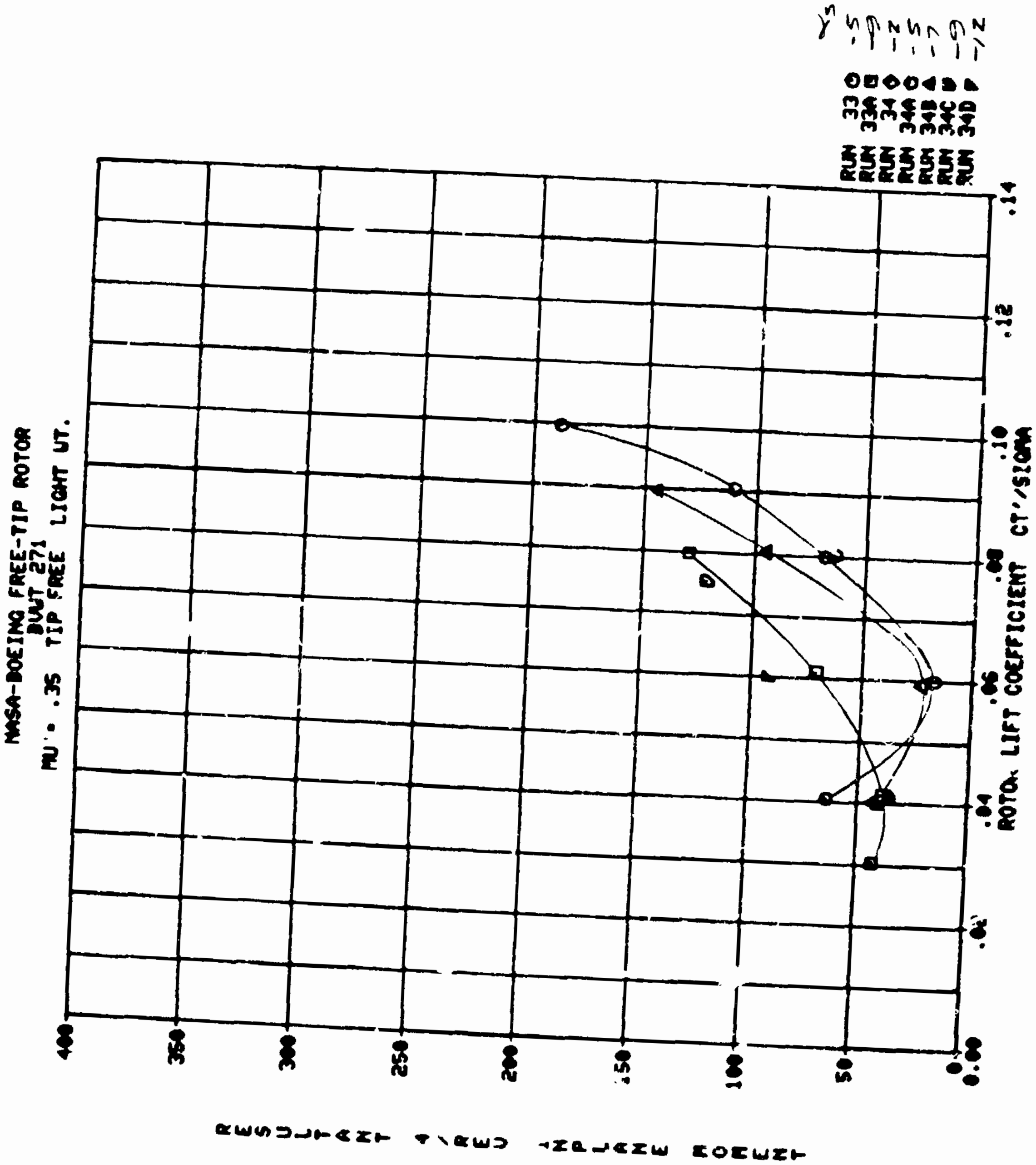
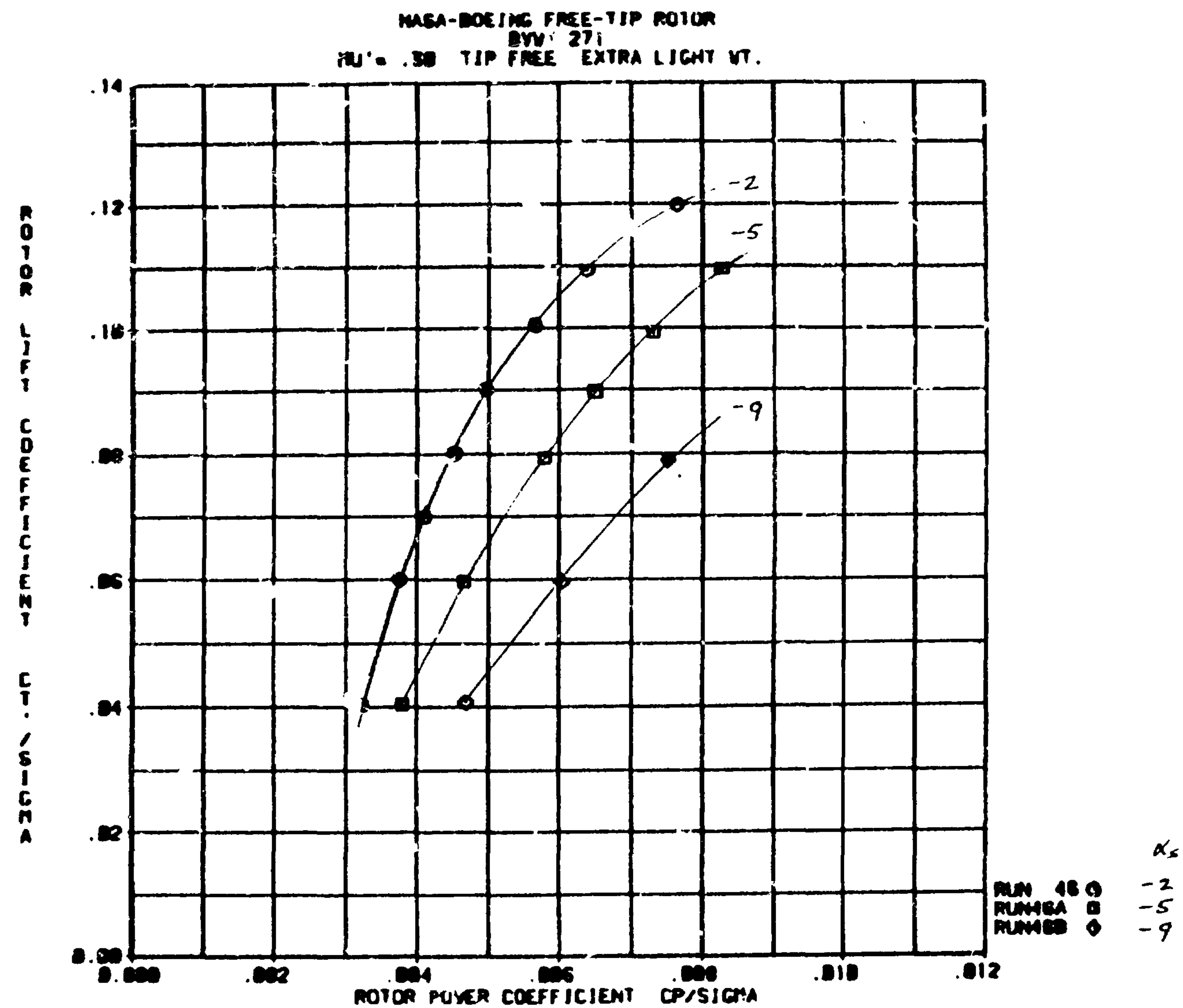
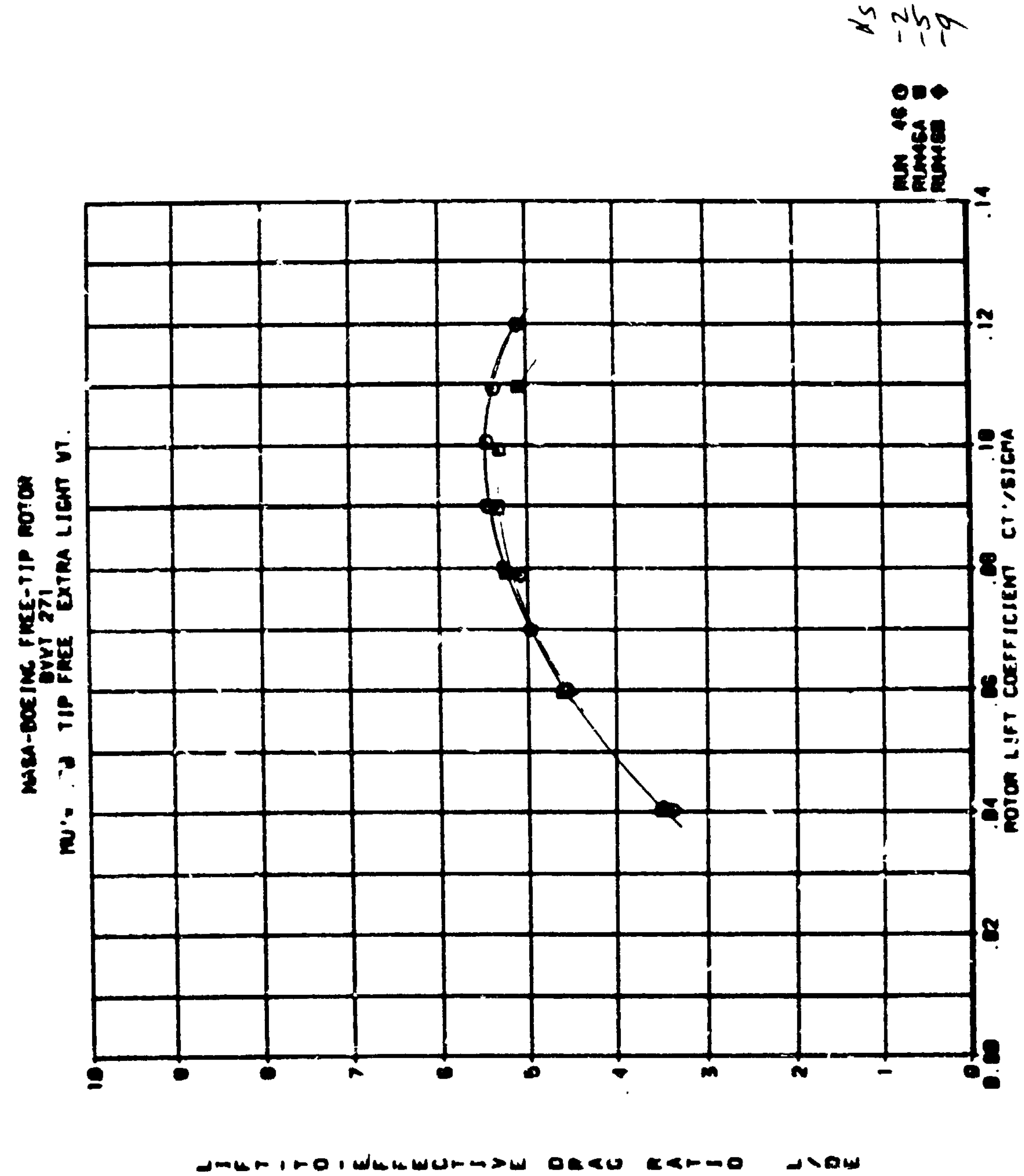



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE EXTRA LIGHT WT.
ROTOR LIFT COEFFICIENT CT/SIGMA
ROTOR POWER COEFFICIENT CP/SIGMA
.14
.12
.10
.08
.06
.04
.02
0.00
0.000
.002
.004
.006
.008
.010
.012
-2
-5
-9
α_s
RUN 46 -2
RUN46A -5
RUN46B -9


NASA-BOEING FREE-TIP ROTOR
BVWT 271
TIP FREE EXTRA LIGHT WT.
RUN 46
RUN46A
RUN46B
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
1
2
3
4
5
6
7
8
9
10

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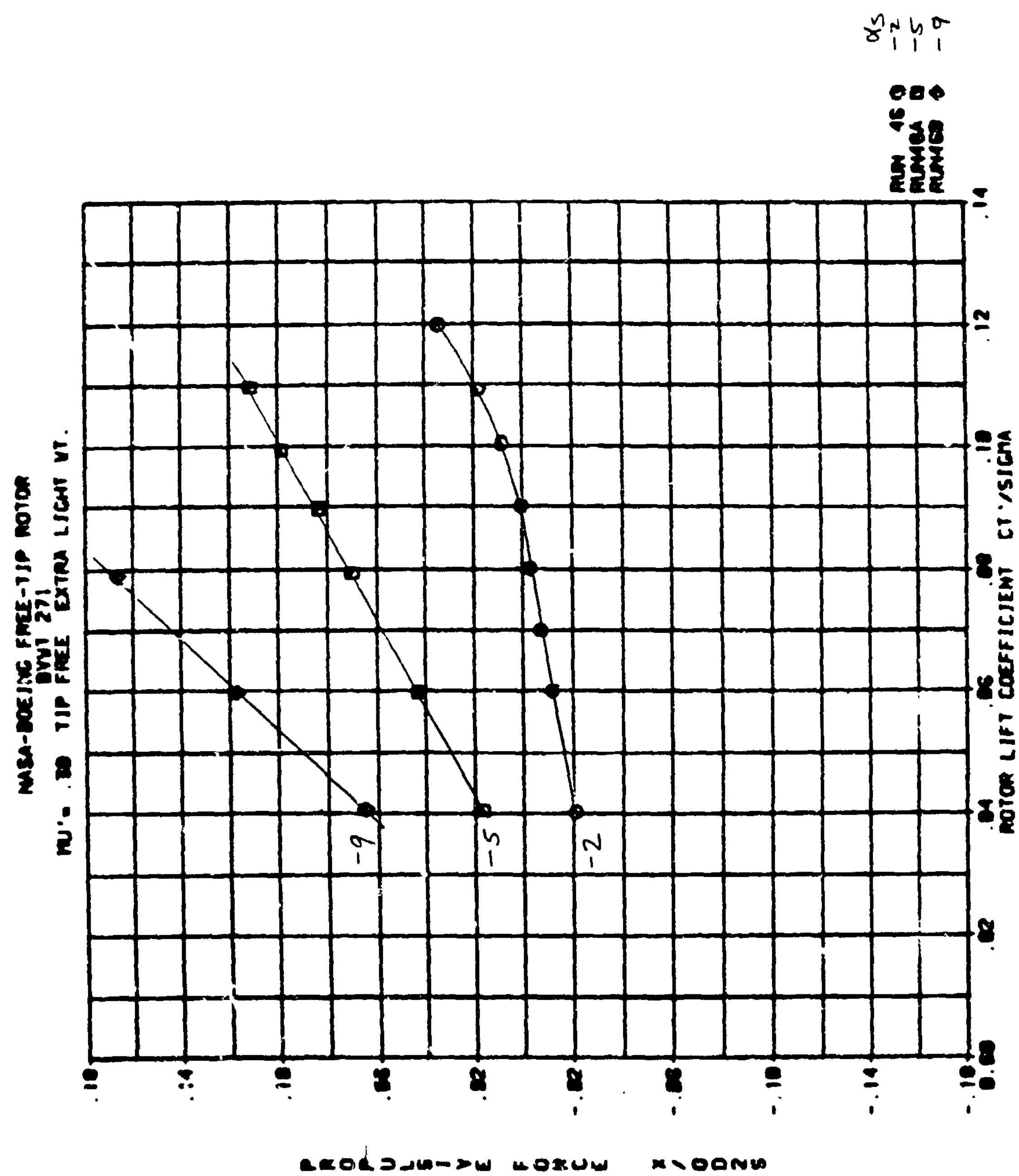

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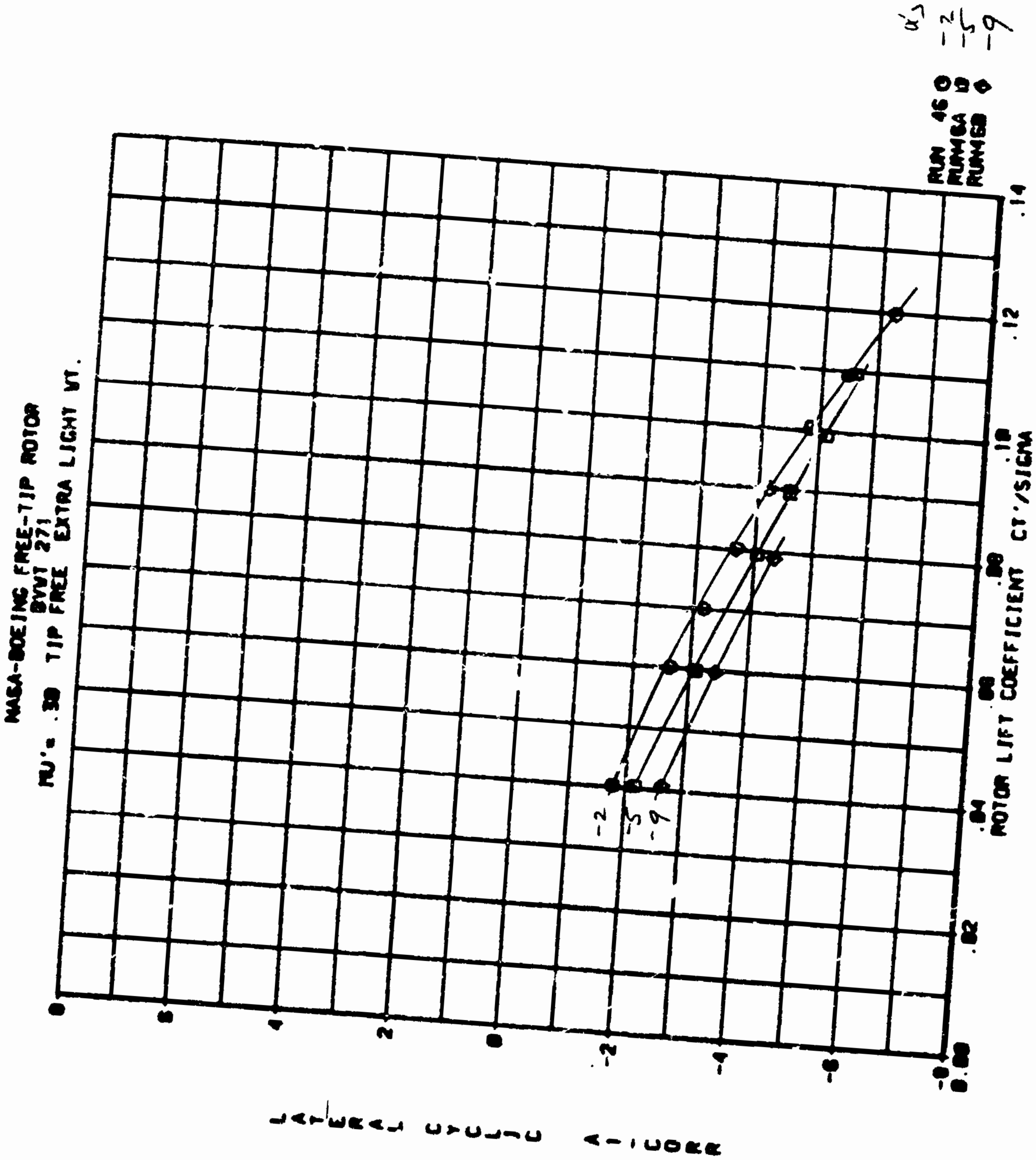

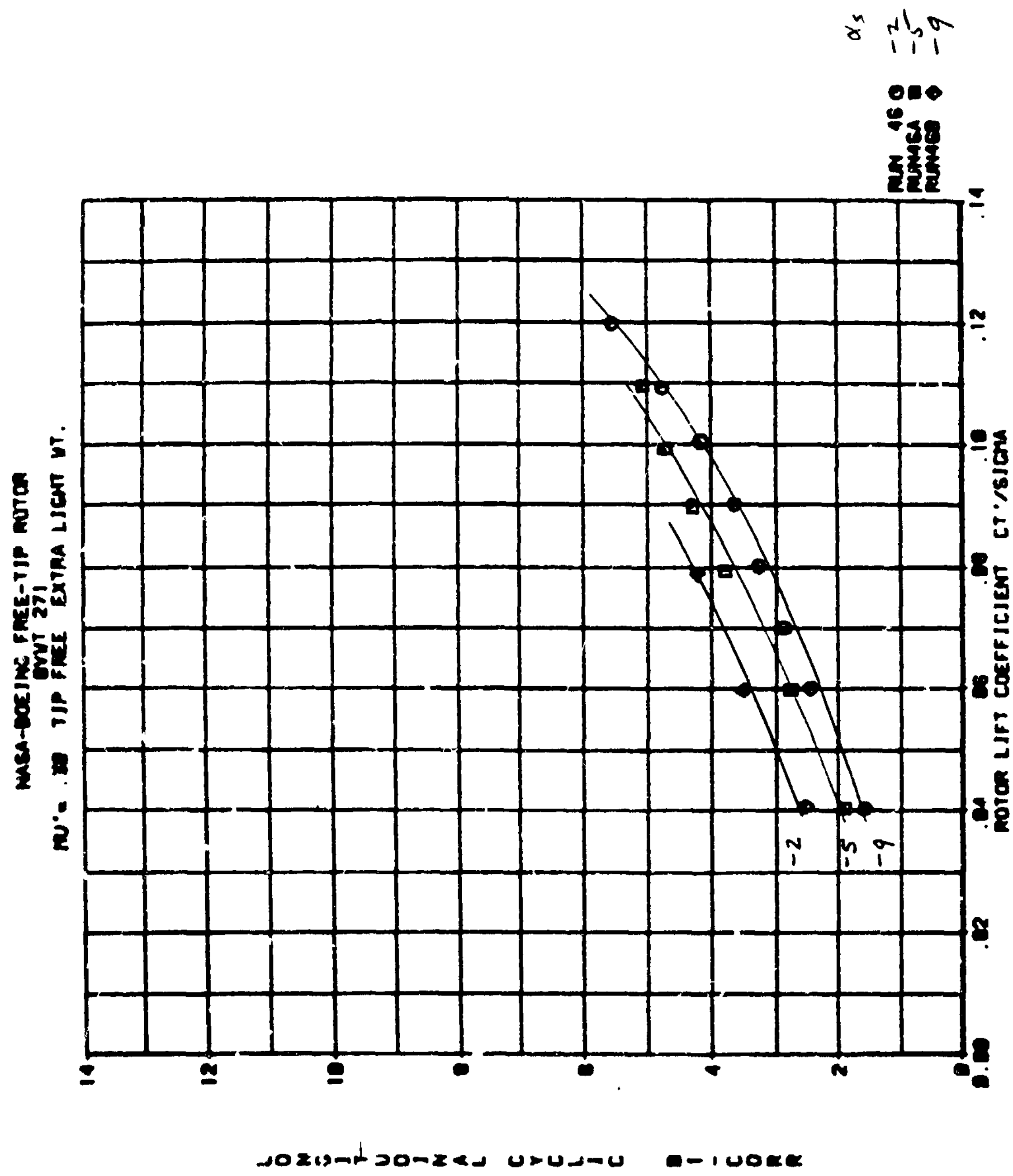

NASA-BOEING FREE-TIP ROTOR
BVWT 271
TIP FREE EXTRA LIGHT WT.
ROTOR LIFT COEFFICIENT CT'/SIGMA
RUN 46
RUN46A
RUN46B
-2
-5
-9

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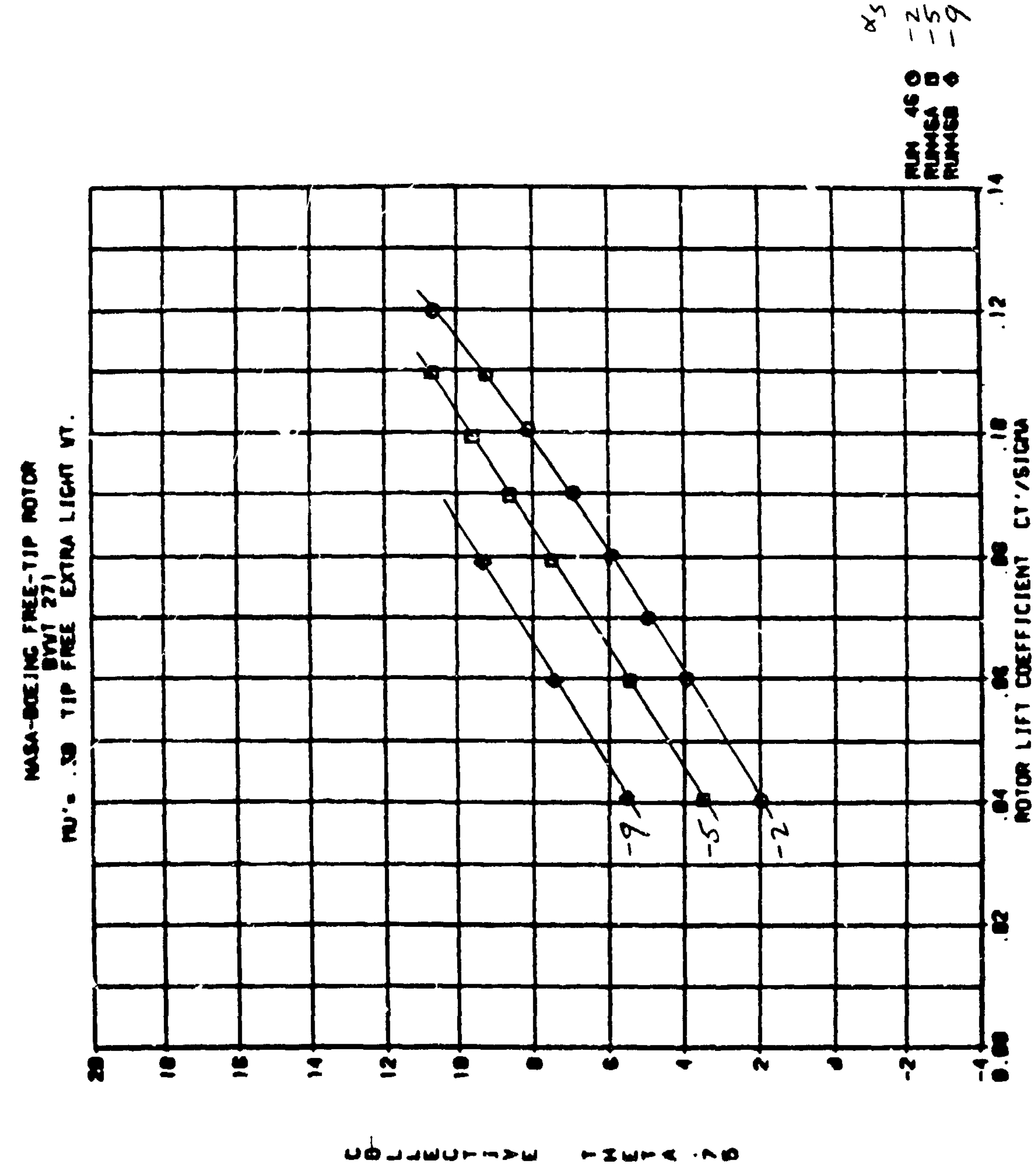
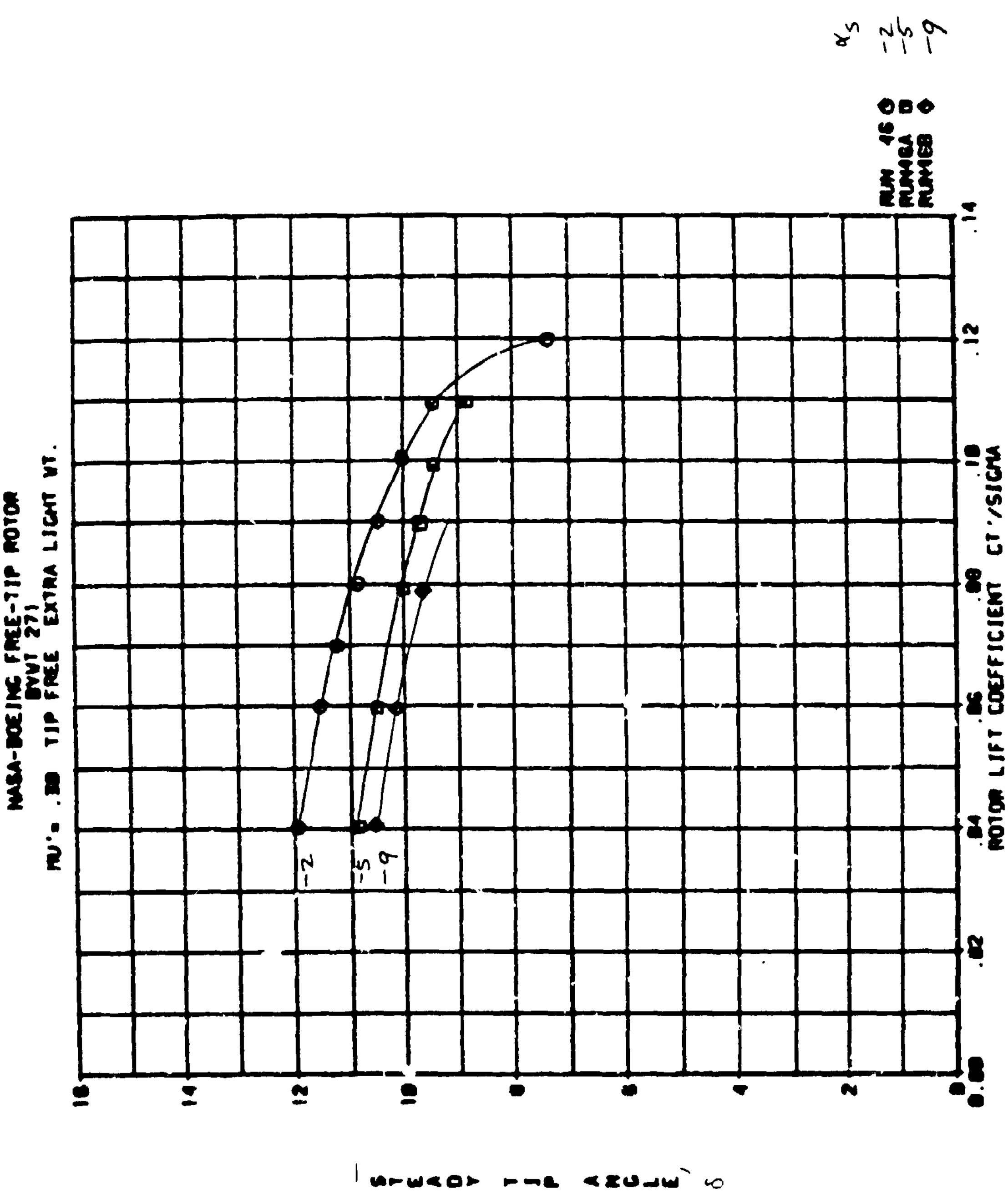
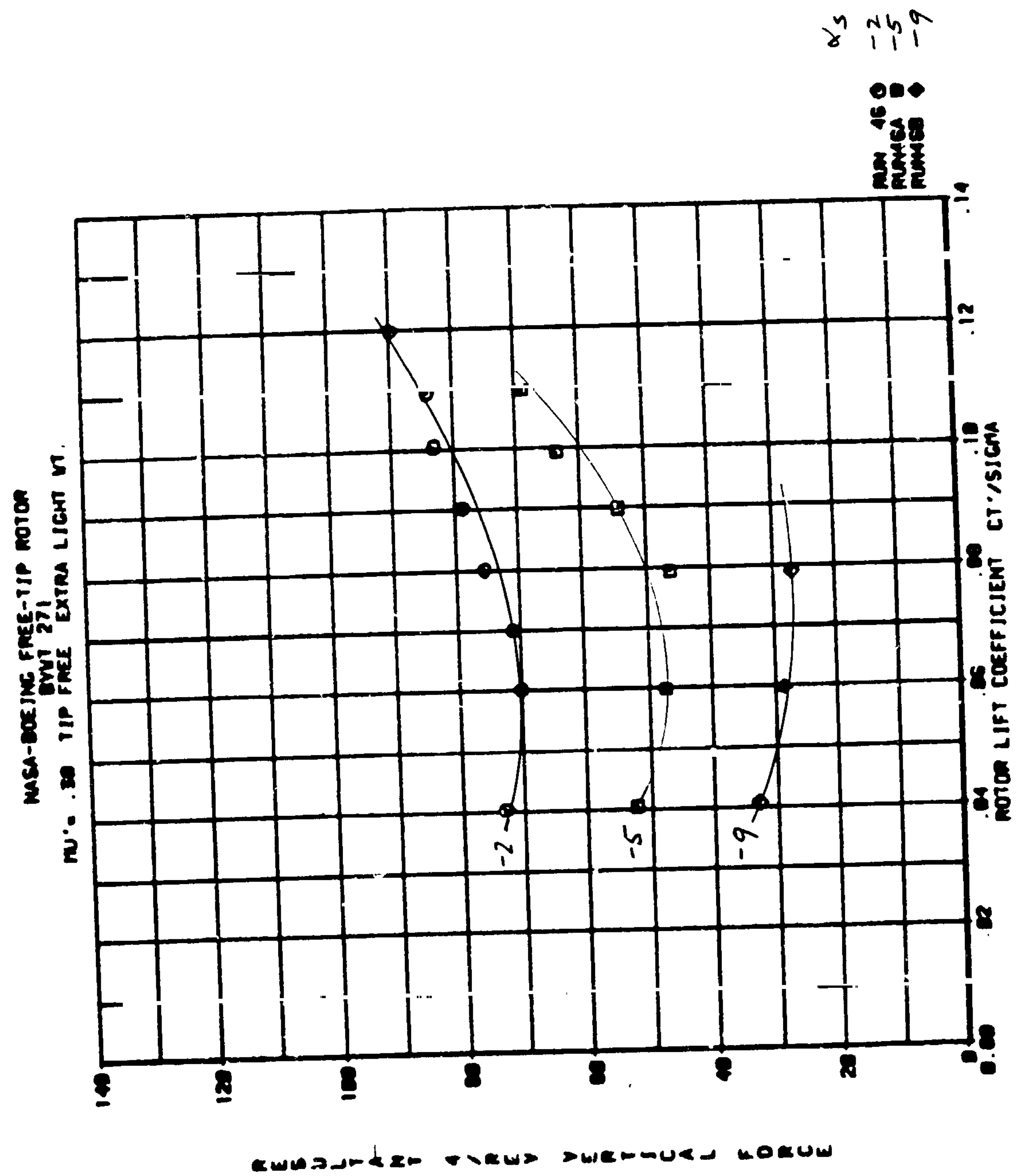



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .38 TIP FREE EXTRA LIGHT WT.
RUN 46
RUN49A
RUN49B
αs -2 -5 -9
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
16
14
12
10
8
6
4
2
0
-2
-5
-9


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE EXTRA LIGHT WT.
RUN 46
RUN46A
RUN46B
δs
-2
-5
-9
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
140
120
100
80
60
40
20
0

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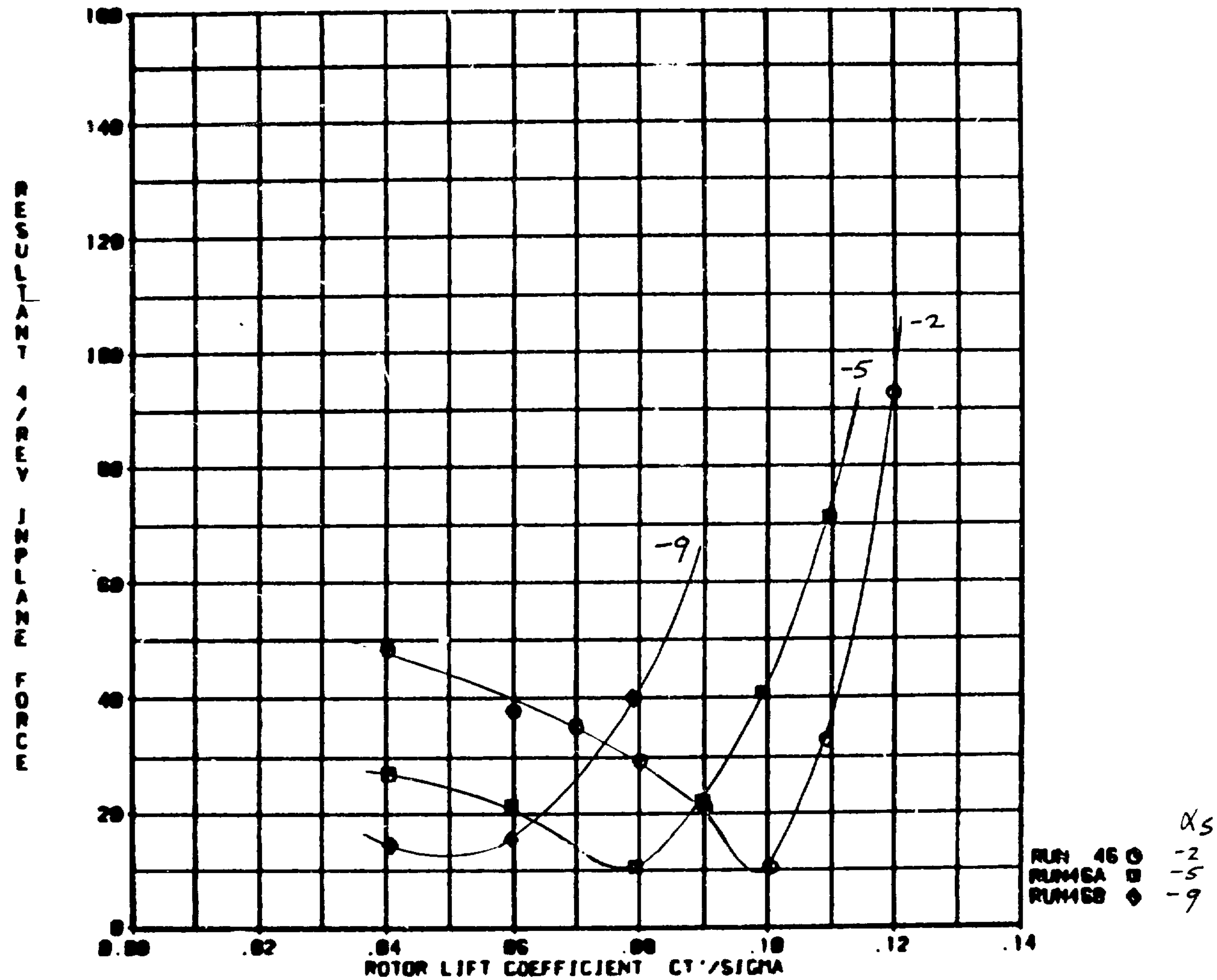
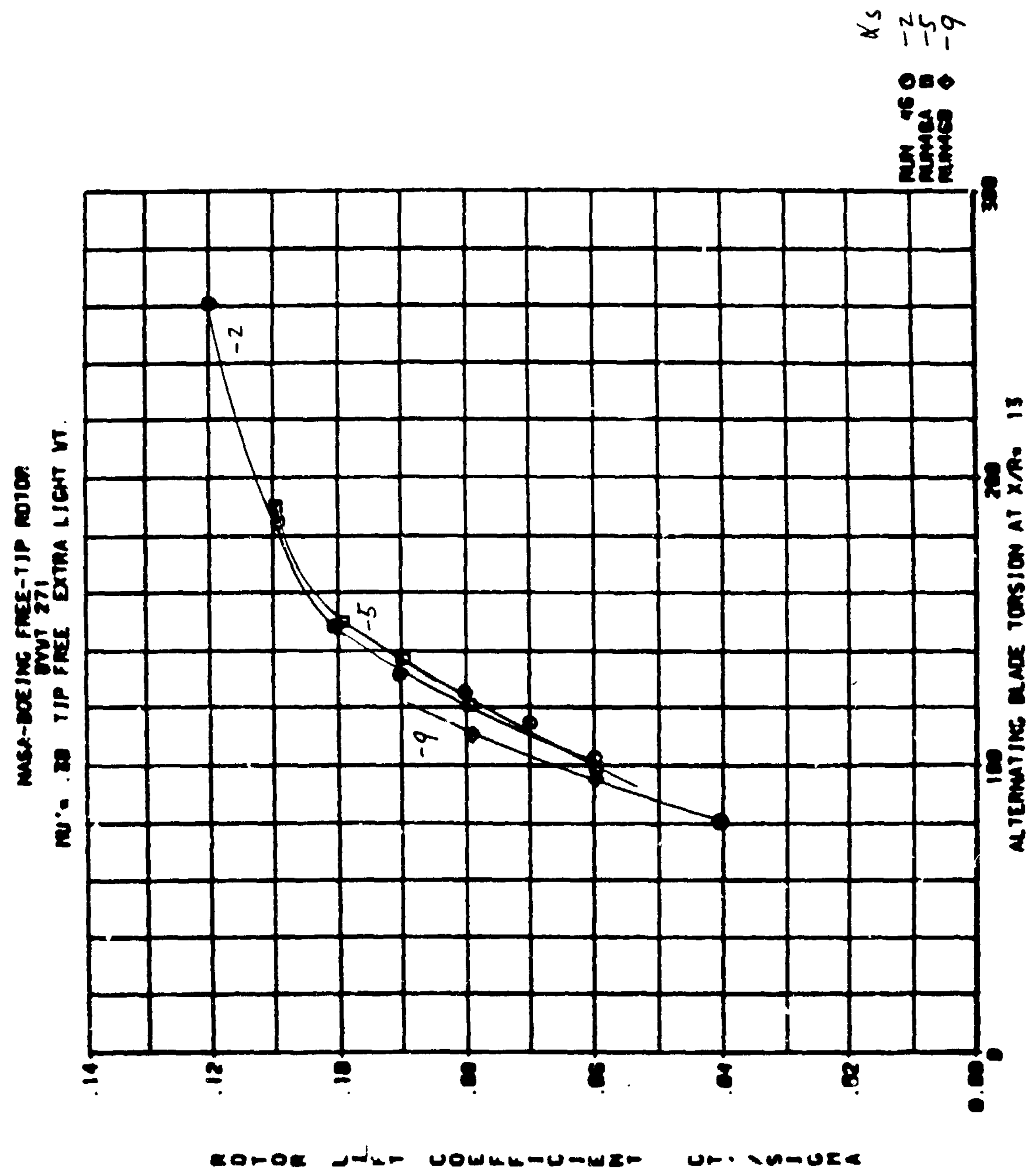
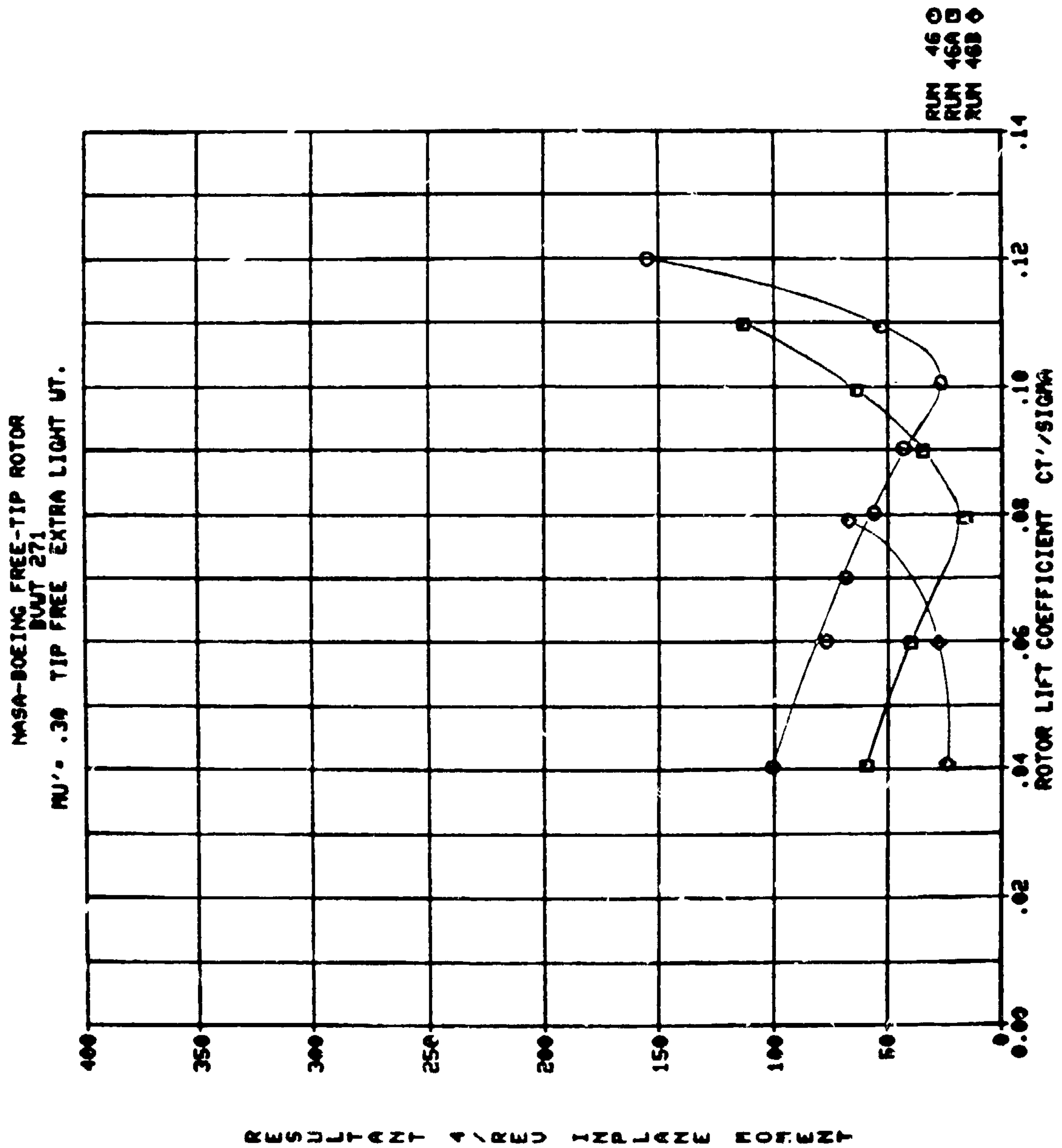
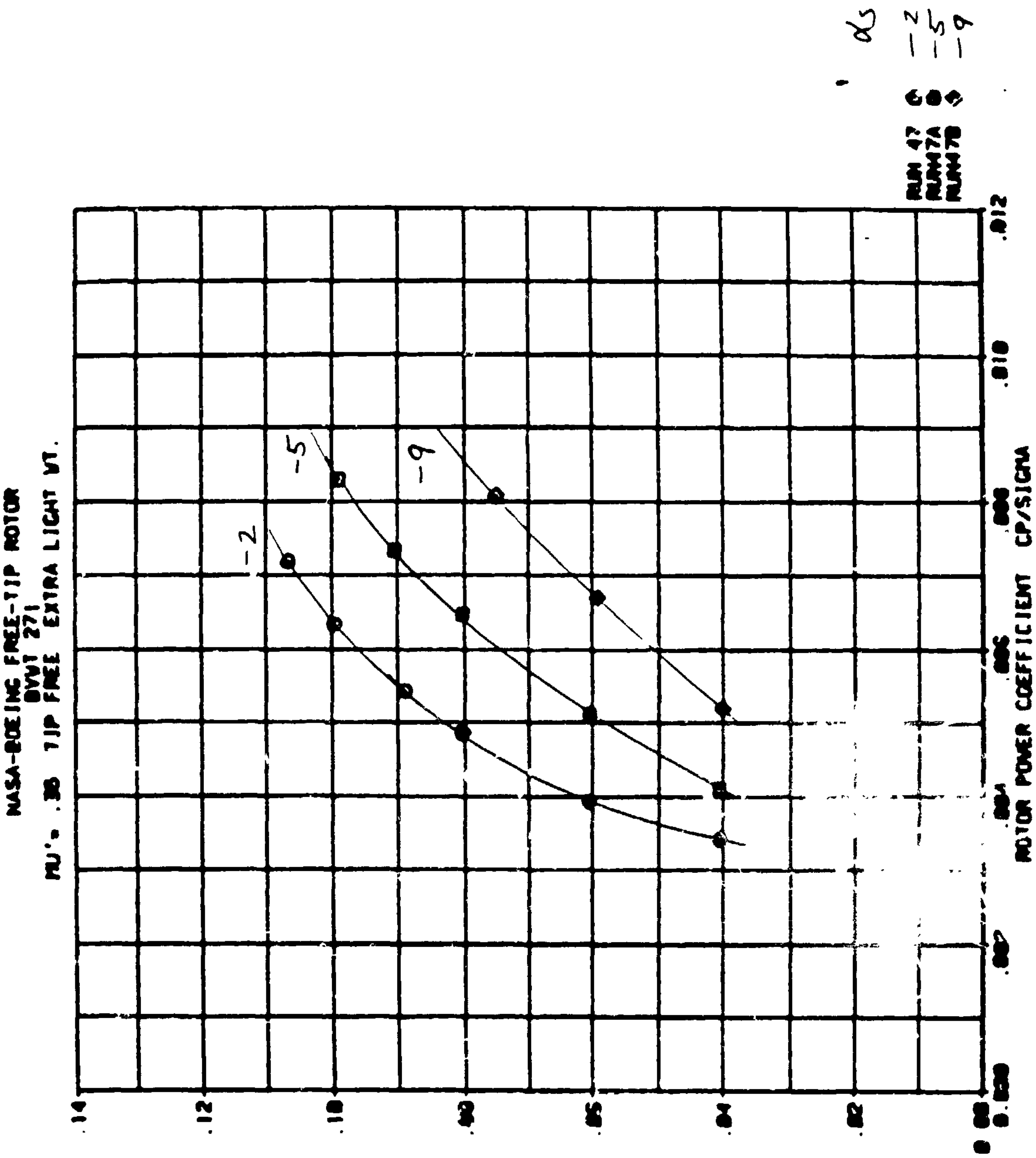
BVWT 271
MU'= .30 TIP FREE EXTRA LIGHT WT.




NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE EXTRA LIGHT WT.
RUN 46 ○ -2
RUN46A □ -5
RUN46B ◇ -9
α_s
-2
-5
-9
ALTERNATING BLADE TORSION AT X/R= 13
0
100
200
300
.14
.12
.10
.08
.06
.04
.02
0.00

ORIGIN
OF


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE EXTRA LIGHT WT.
RUN 46
RUN 46A
RUN 46B
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
50
100
150
200
250
300
350
400


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .35 TIP FREE EXTRA LIGHT WT.
ROTOR POWER COEFFICIENT CP/SIGMA
RUN 47
RUN47A
RUN47B
-2
-5
-9

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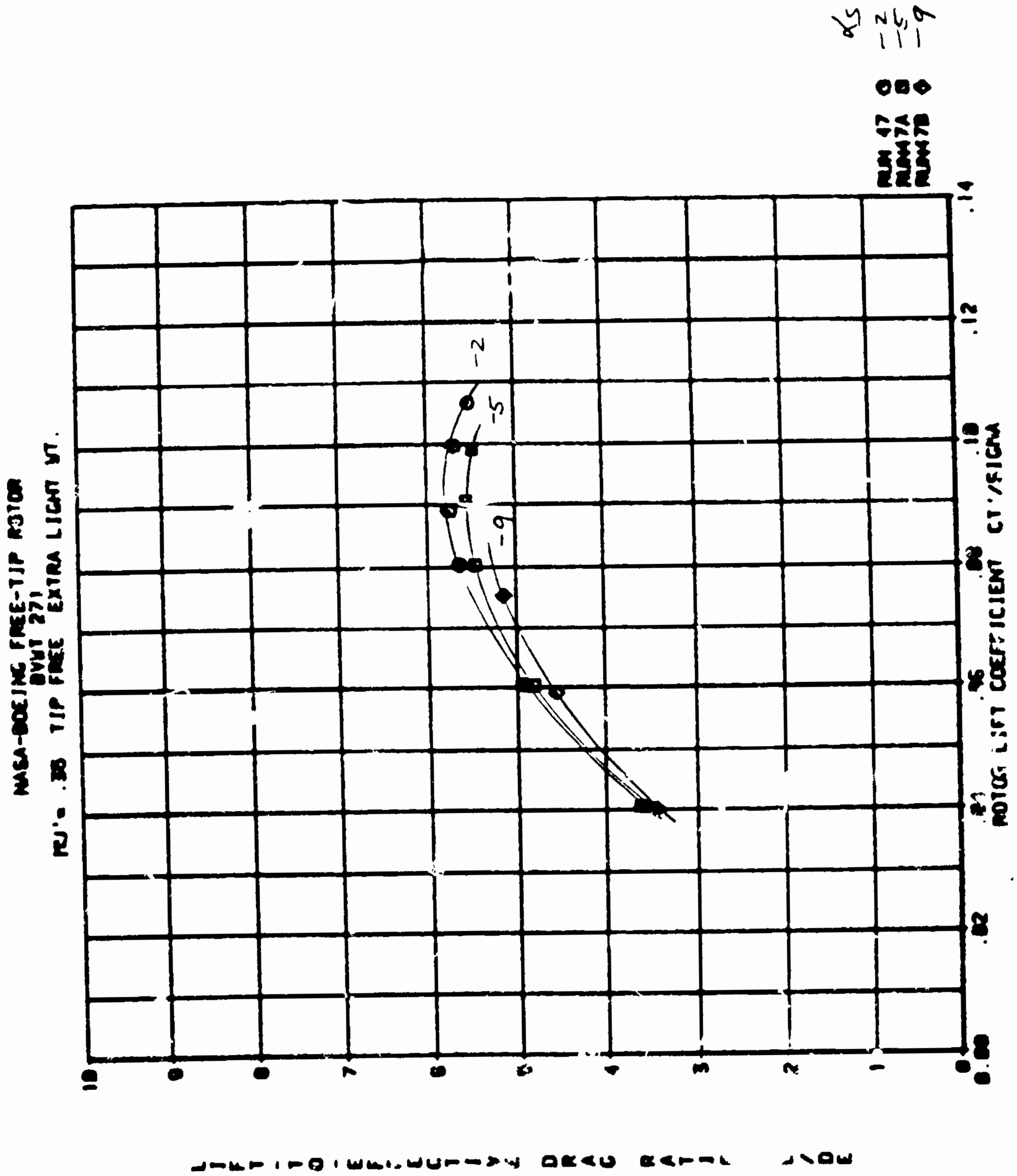

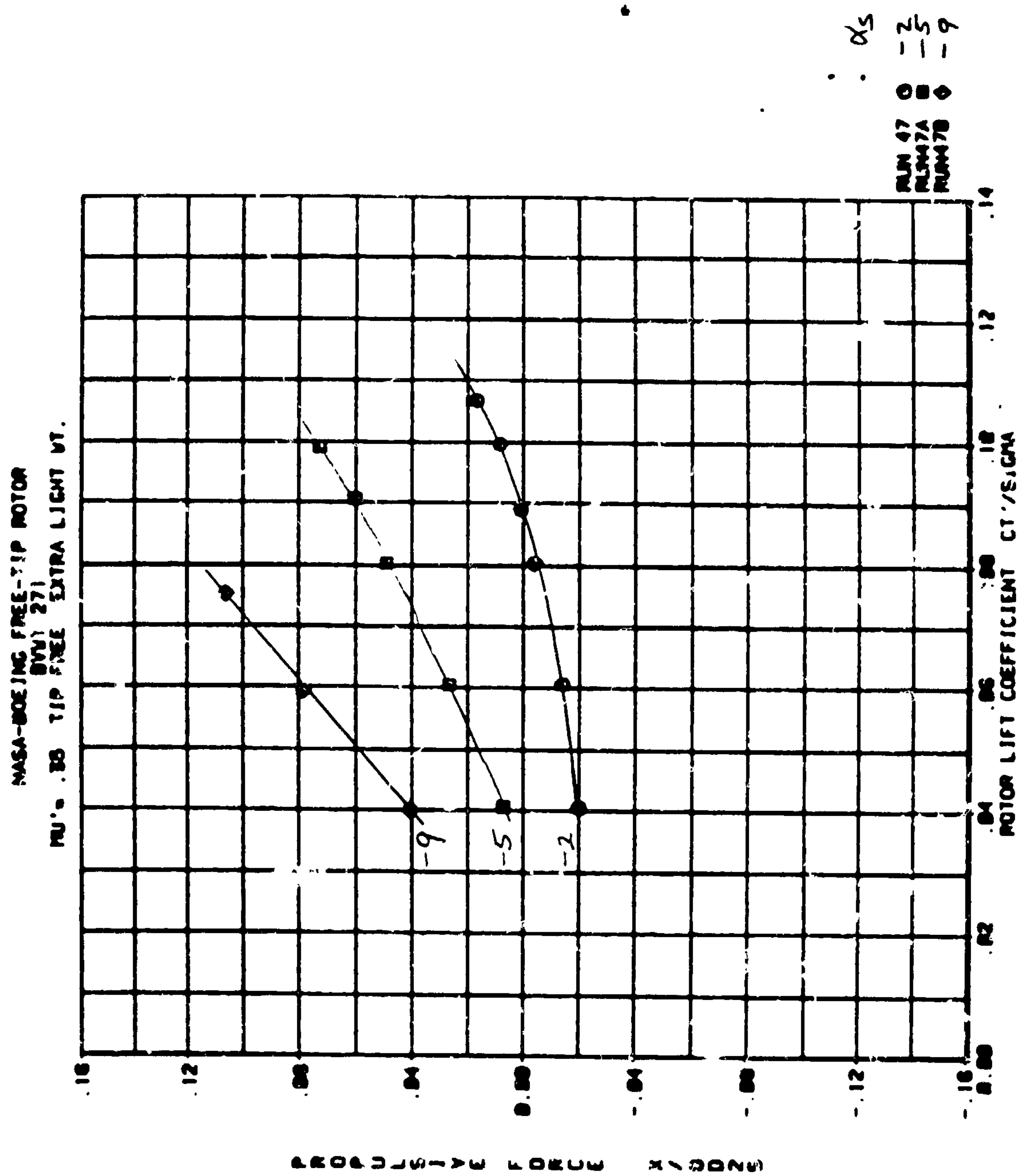
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FREE EXTRA LIGHT WT.
ROTOR LIFT COEFFICIENT CT'/SIGMA
RUN 47
RUN47A
RUN47B
αs
-2
-5
-9

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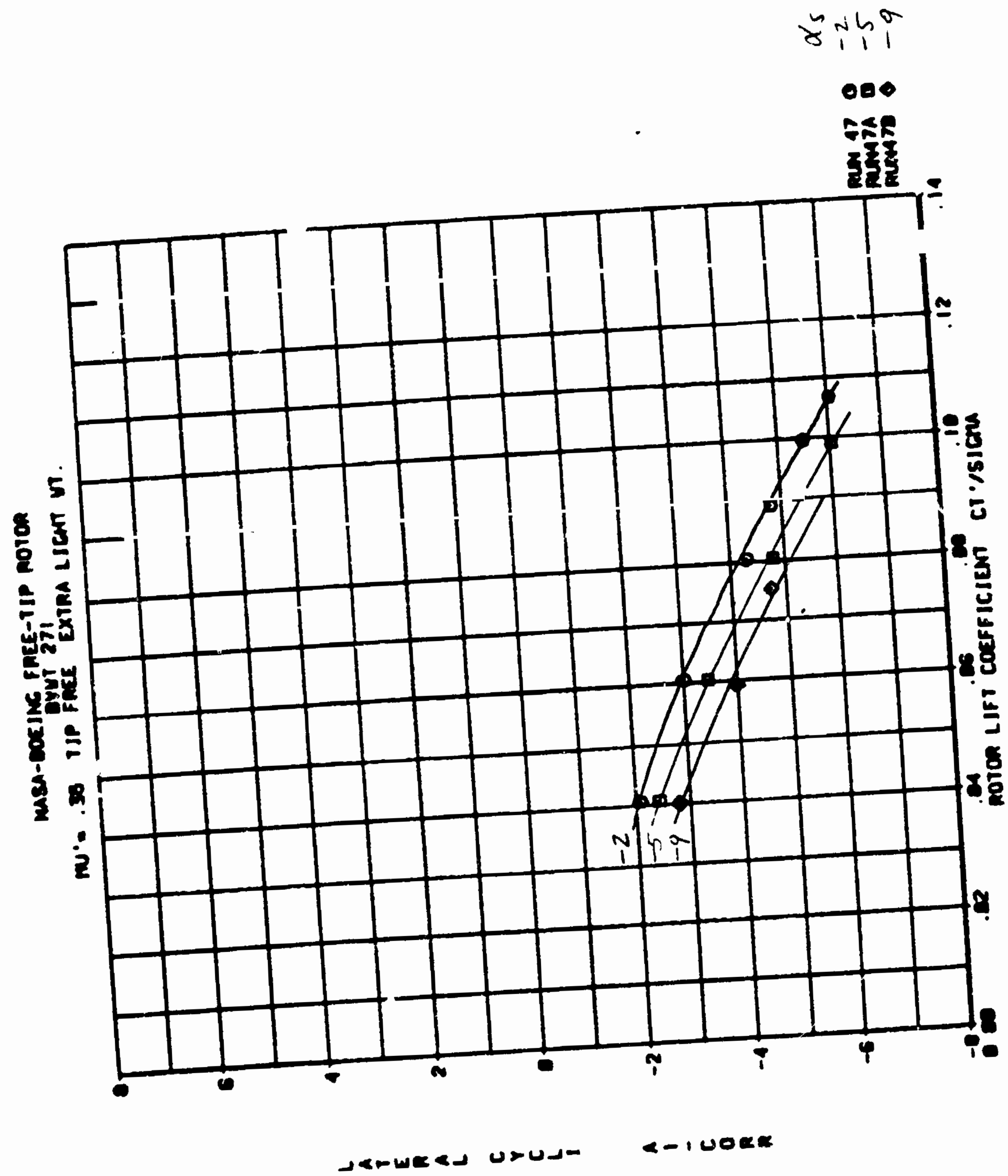

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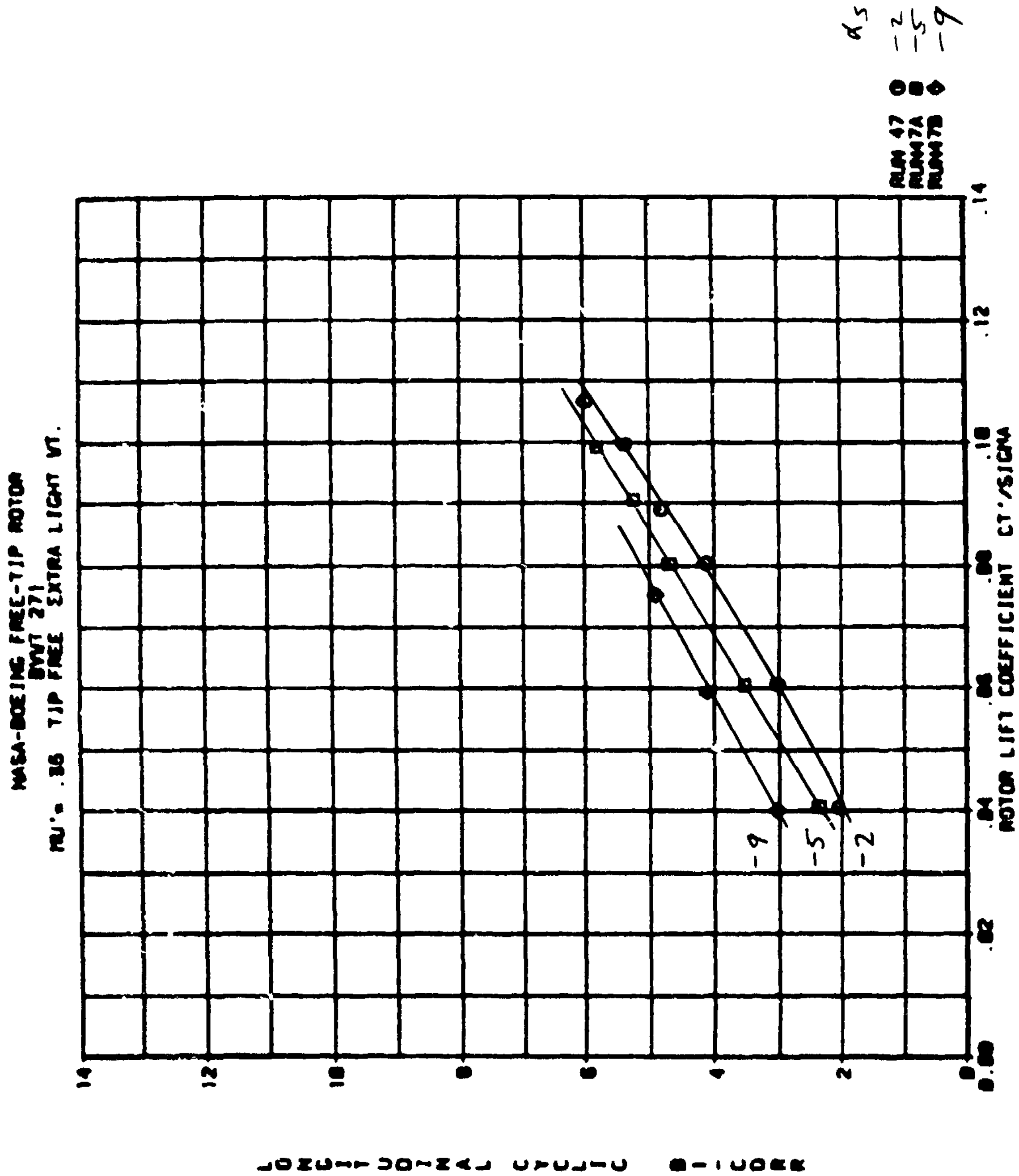

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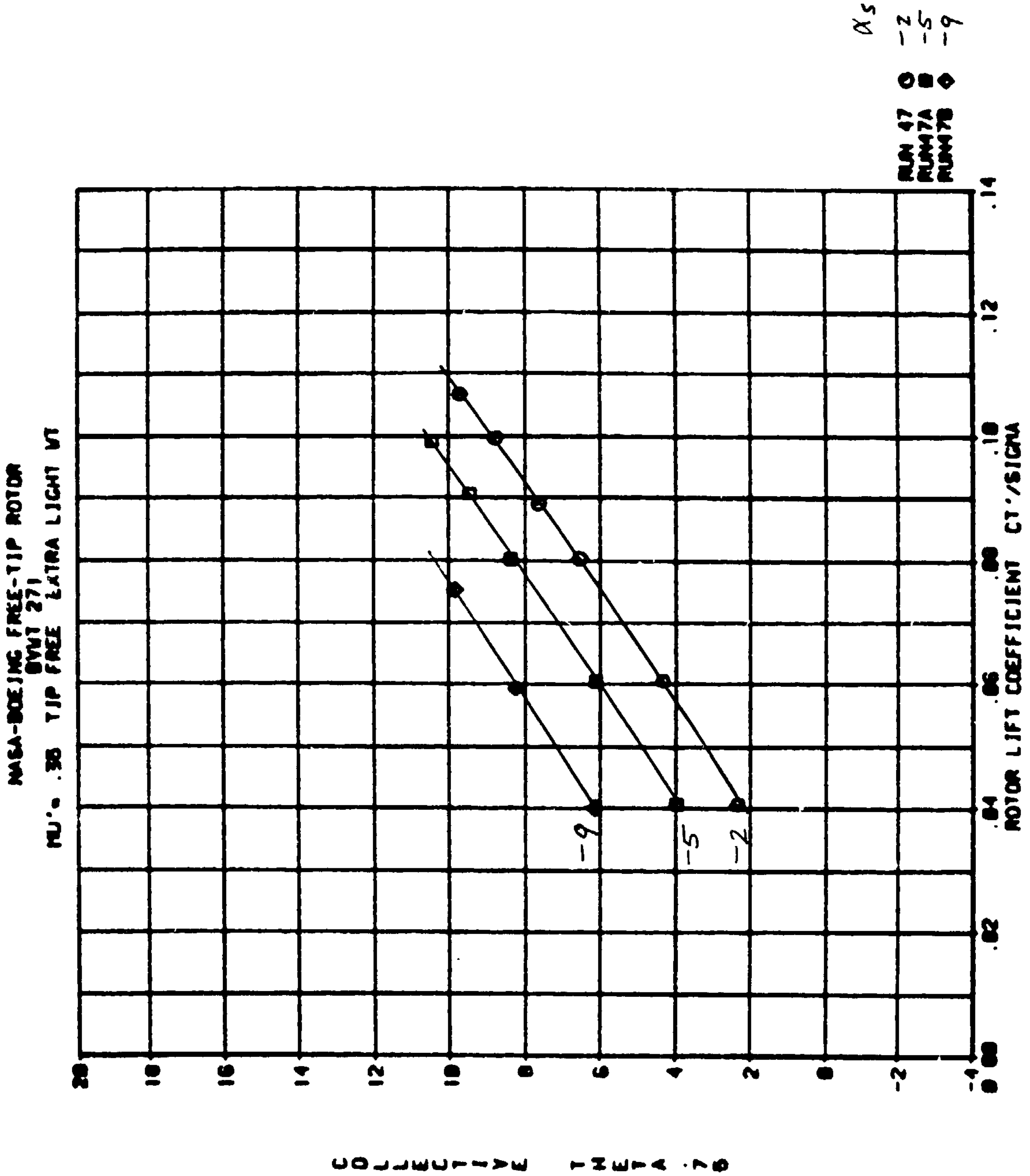

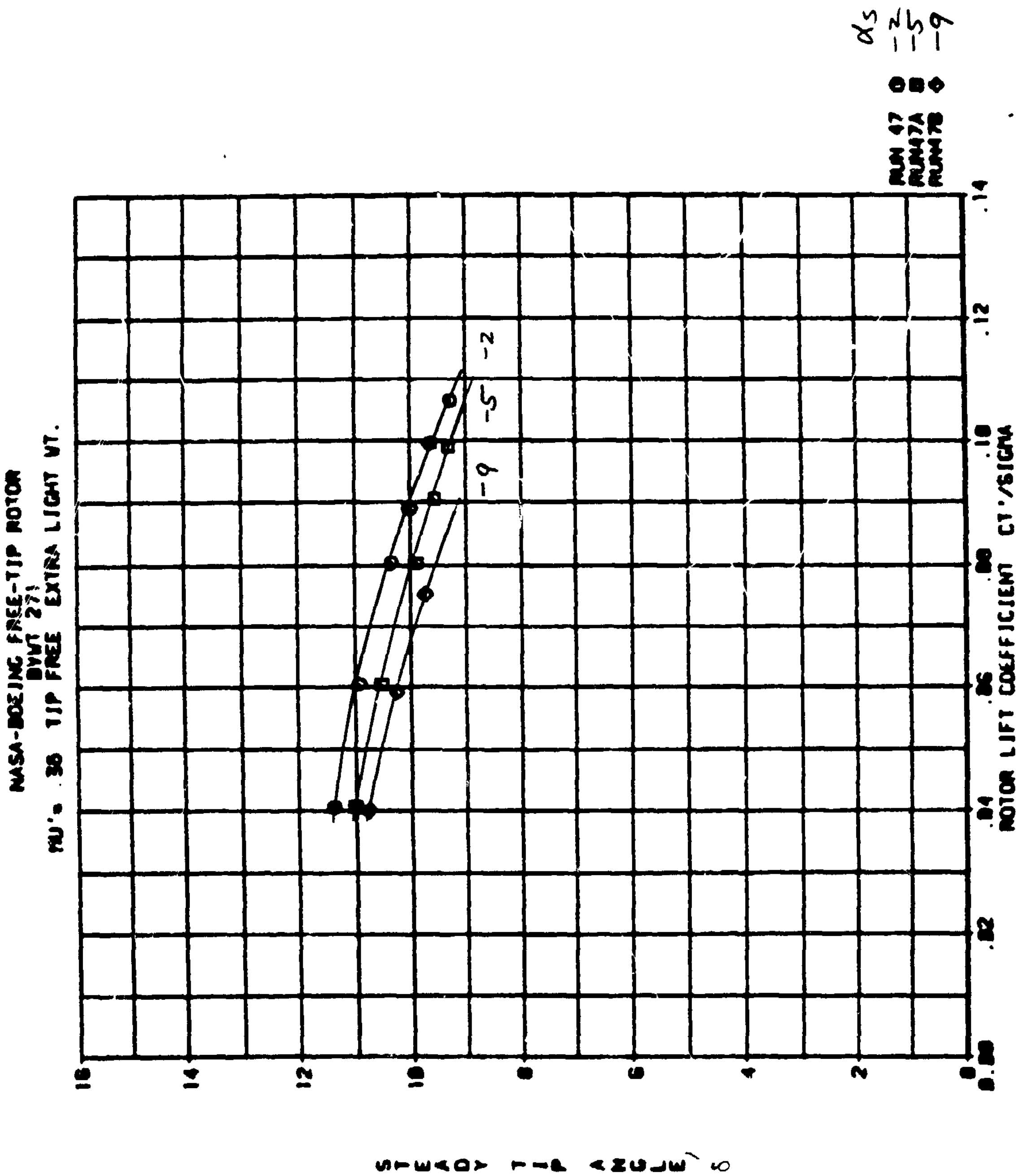
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .36 TIP FREE EXTRA LIGHT WT.
RUN 47
RUN47A
RUN47B
α_s -2 -5 -9
-2
-5
-9
0.00
.02
.04
.06
.08
.10
.12
.14
ROTOR LIFT COEFFICIENT CT'/SIGMA
0
2
4
6
8
10
12
14
16
STEADY TIP ANGLE

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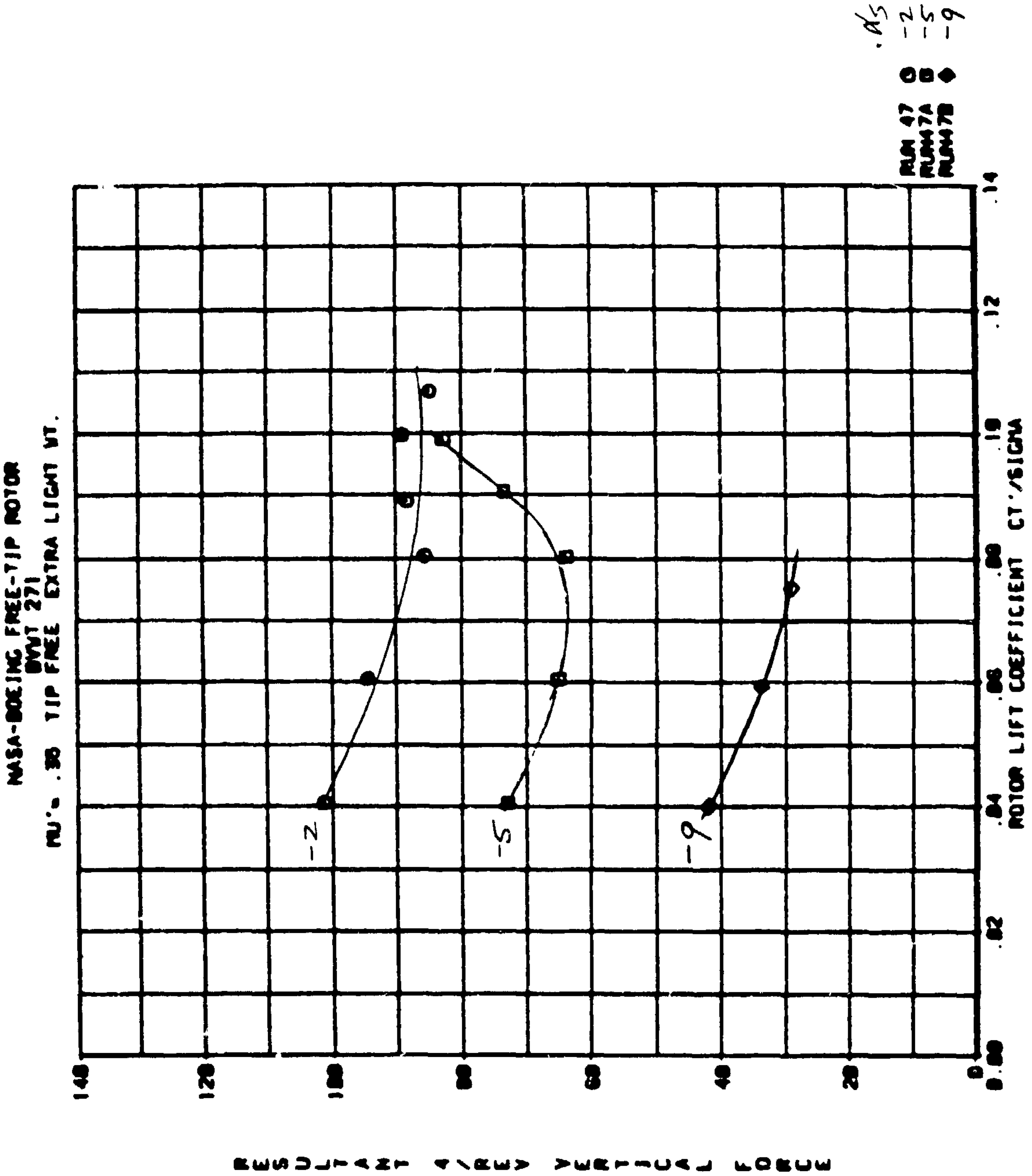

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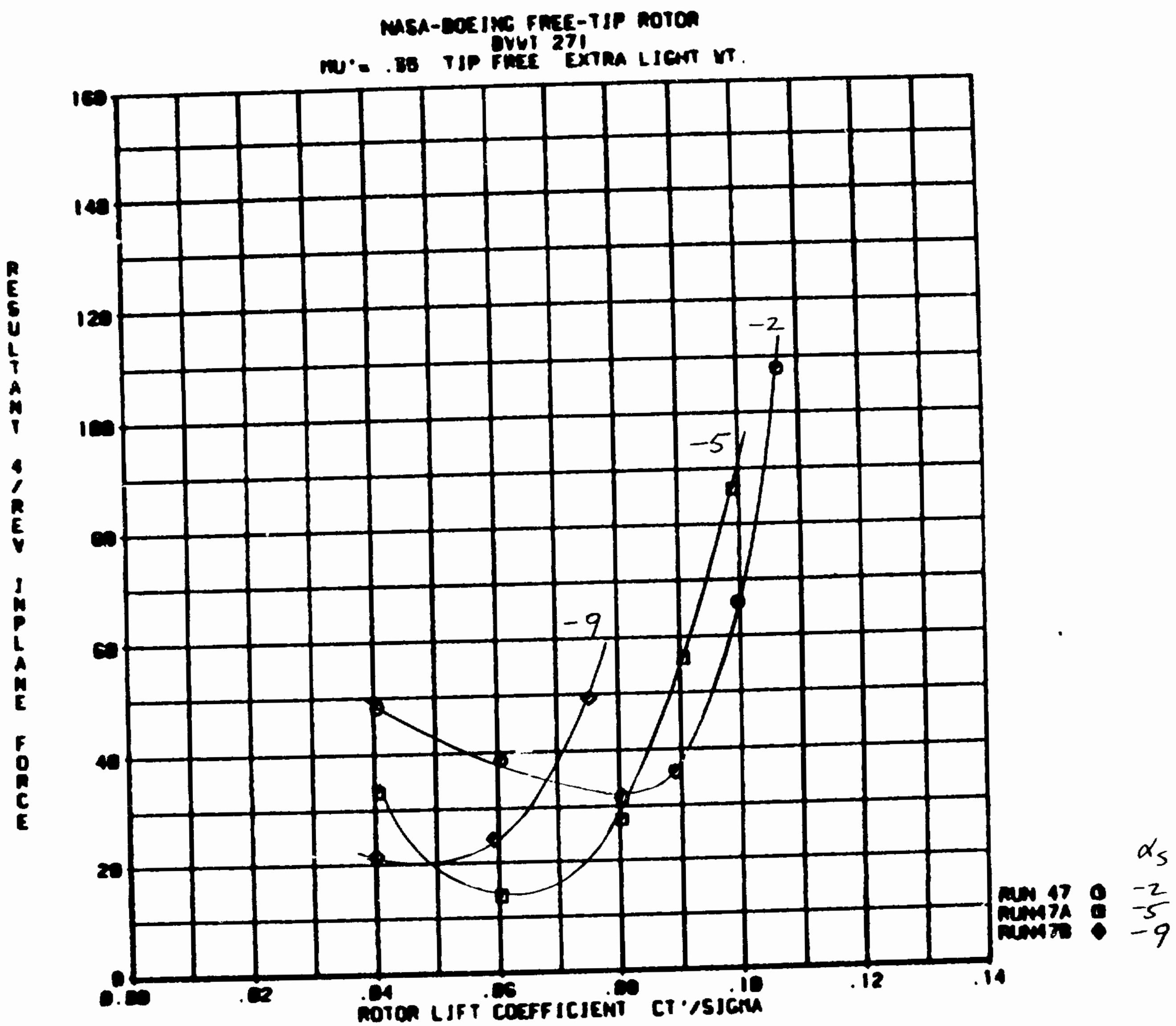

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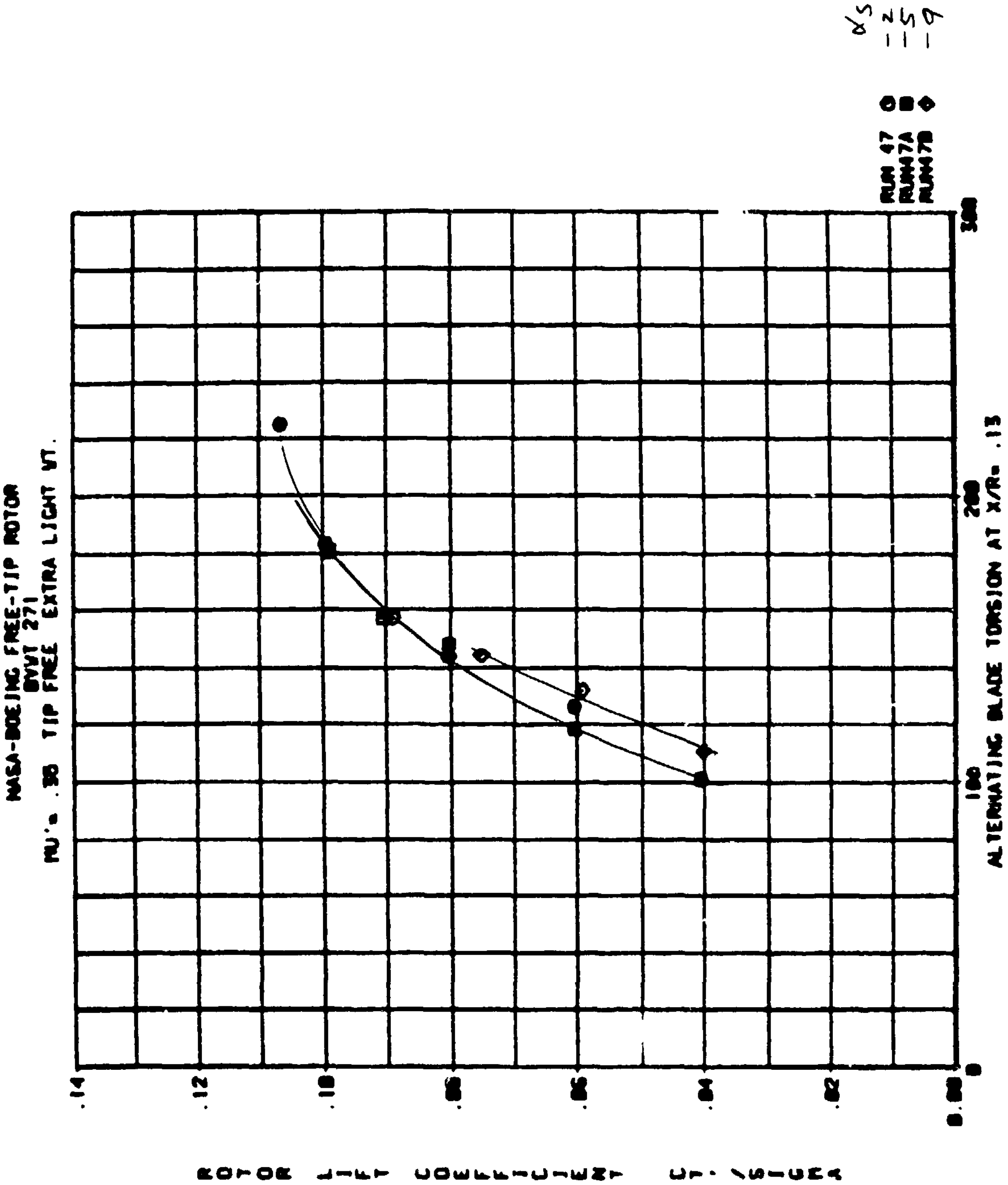
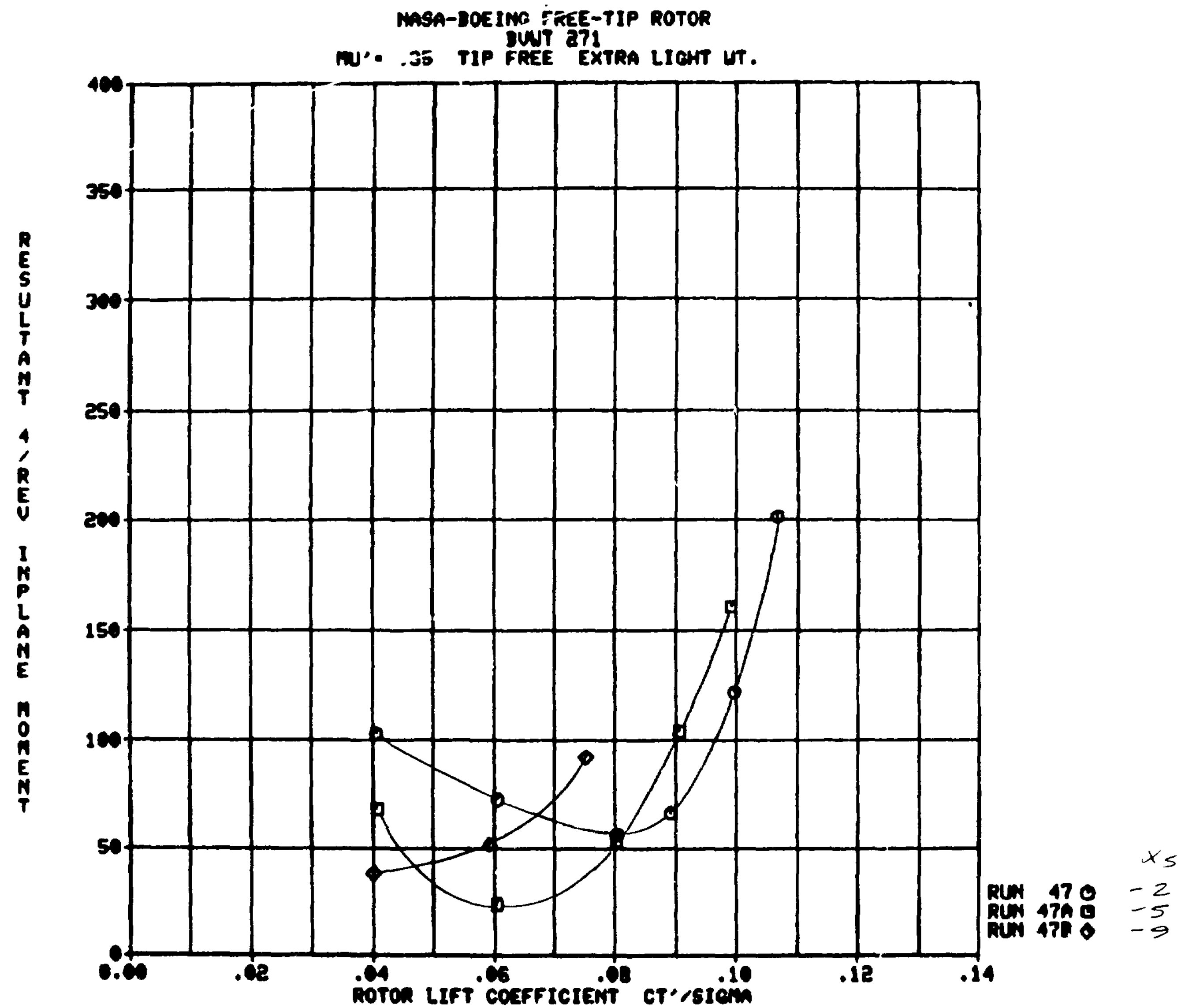
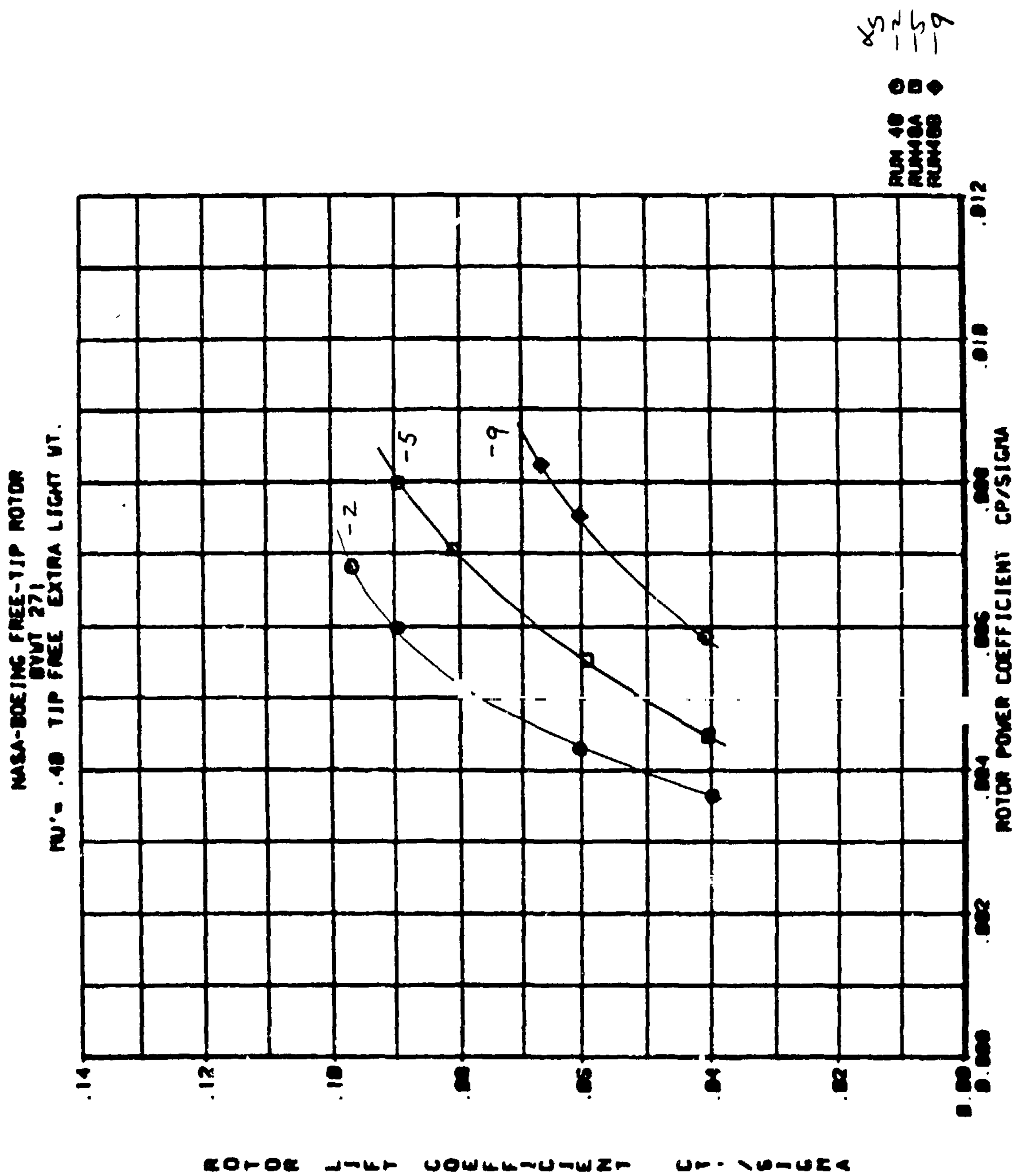



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FREE EXTRA LIGHT WT.
RESULTANT 4/REV INPLANE MOMENT
0
50
100
150
200
250
300
350
400
0.00
.02
.04
.06
.08
.10
.12
.14
ROTOR LIFT COEFFICIENT CT'/SIGMA
RUN 47
RUN 47A
RUN 47B
xs
-2
-5
-9

QUALITY



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .40 TIP FREE EXTRA LIGHT WT.
RUN 40
RUN40A
RUN40B
-2
-5
-9
.14
.12
.10
.08
.06
.04
.02
0.00
0.000
.002
.004
.006
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.010
.012
ROTOR POWER COEFFICIENT CP/SIGMA

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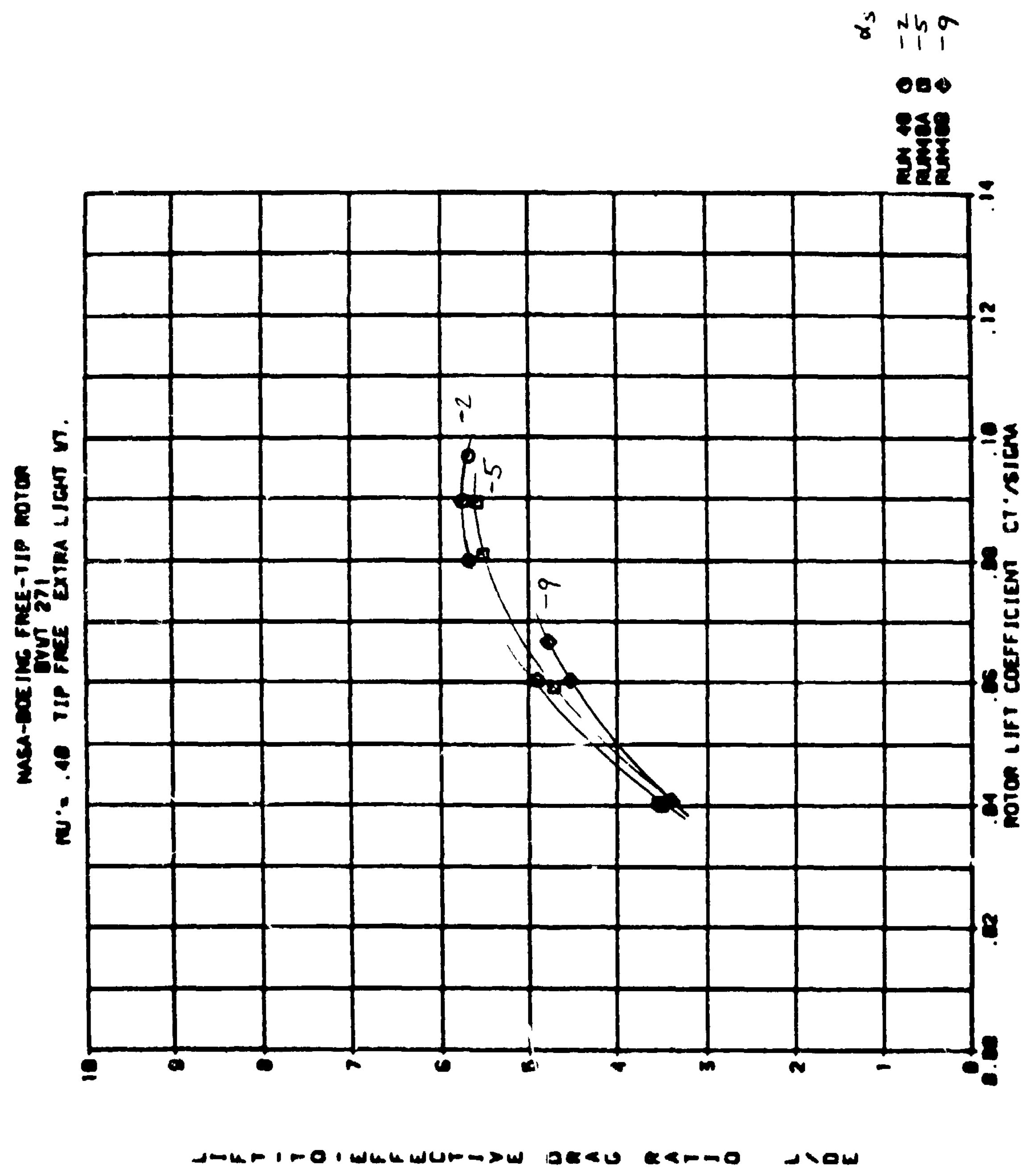

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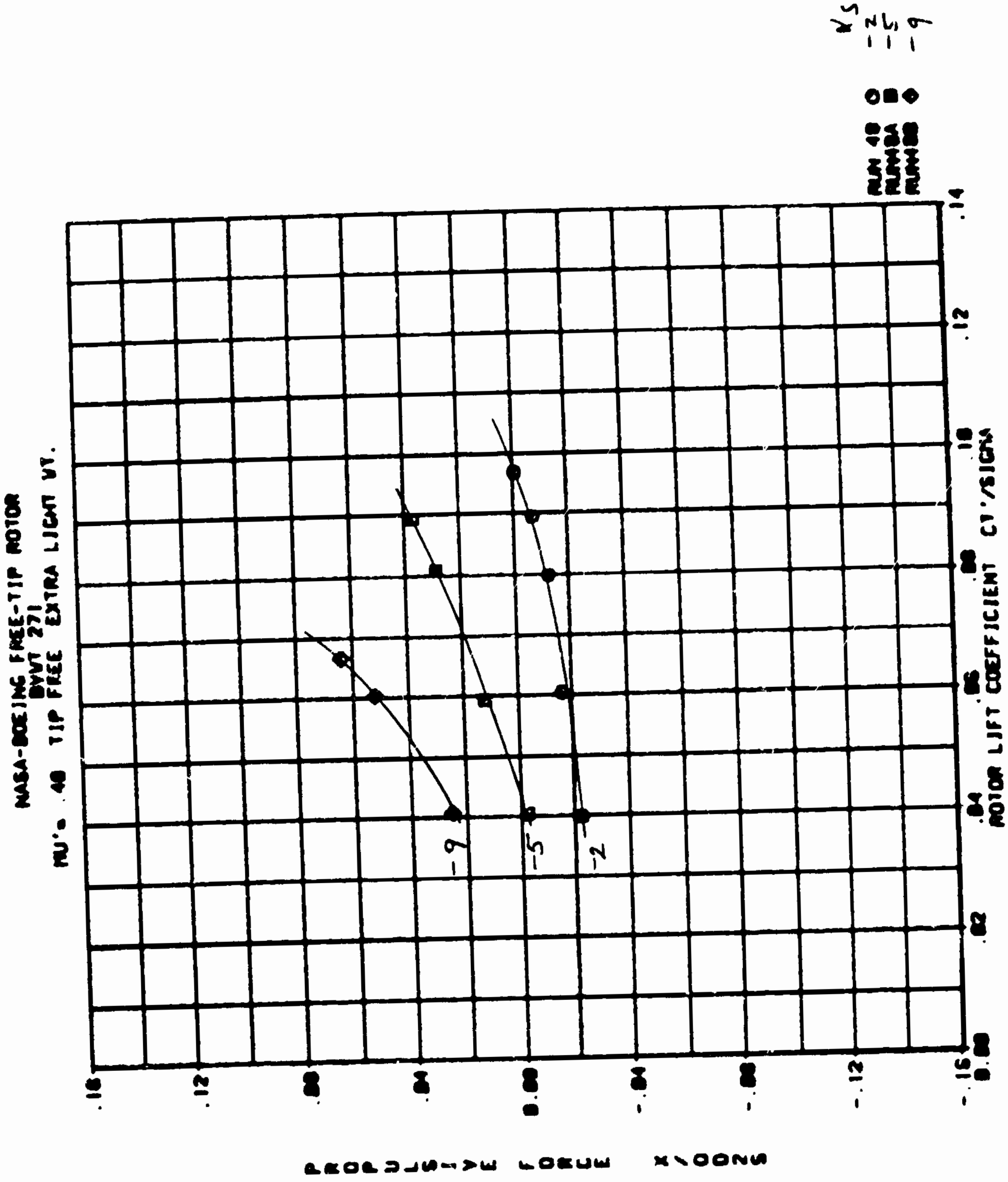

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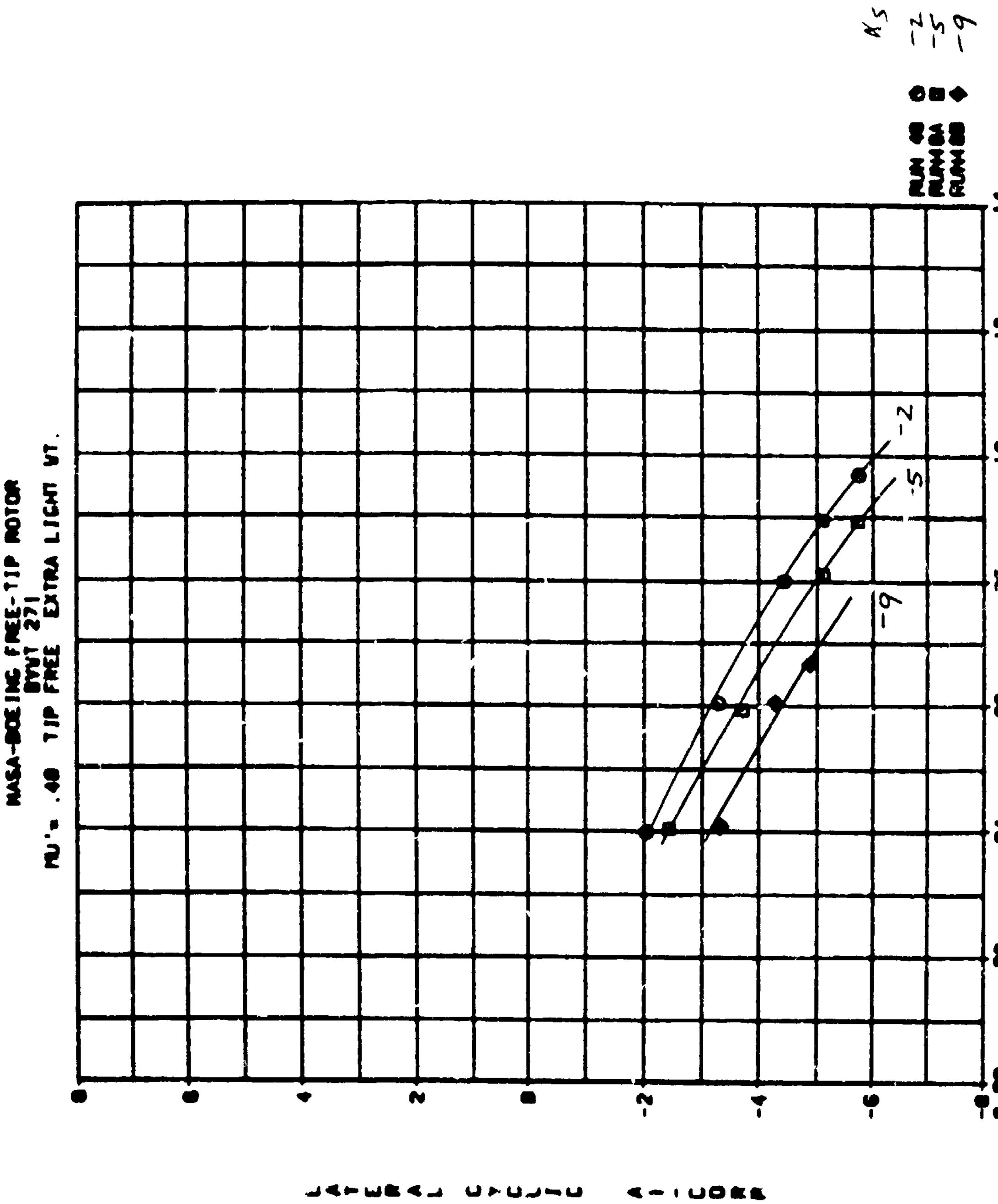

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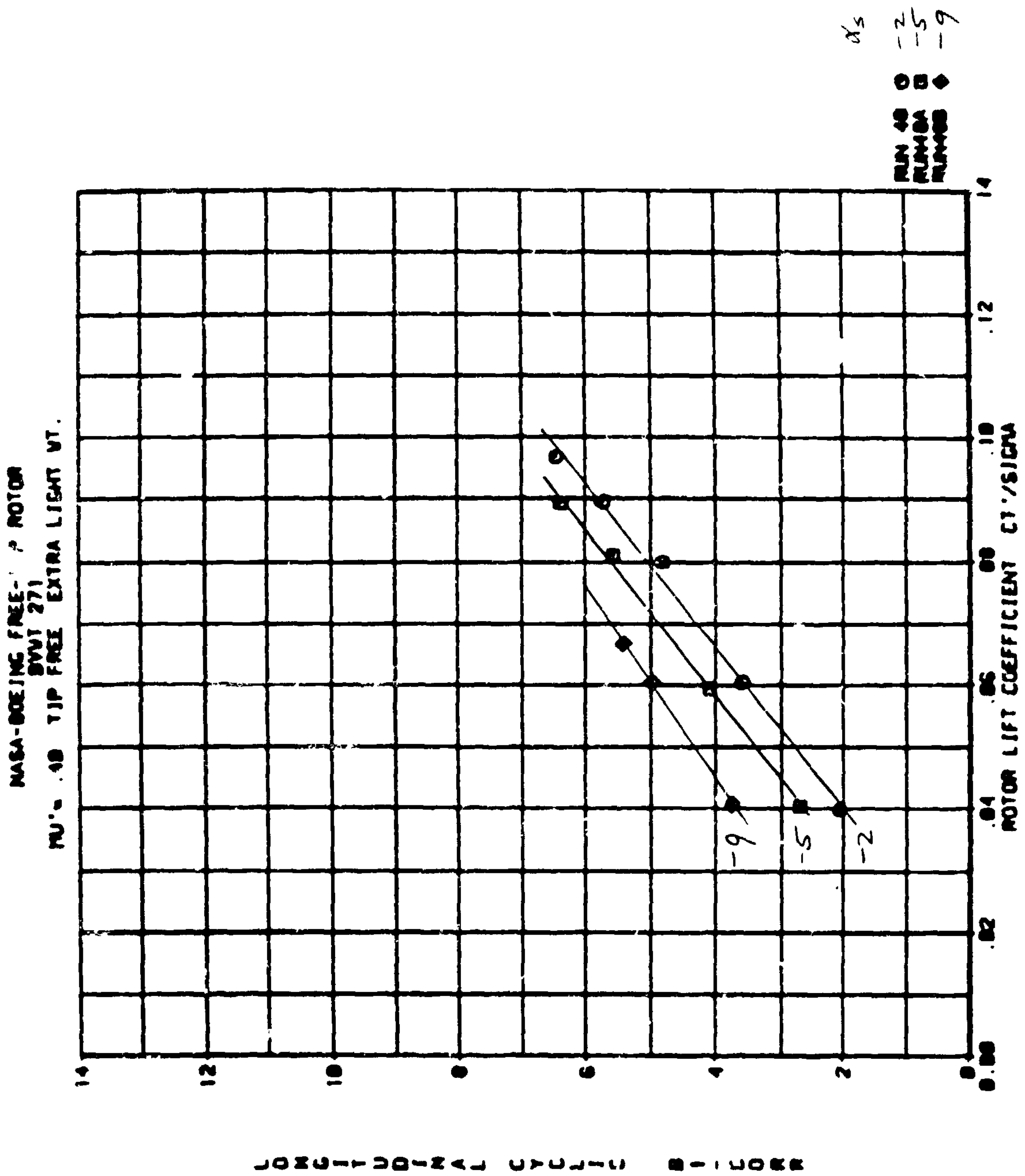

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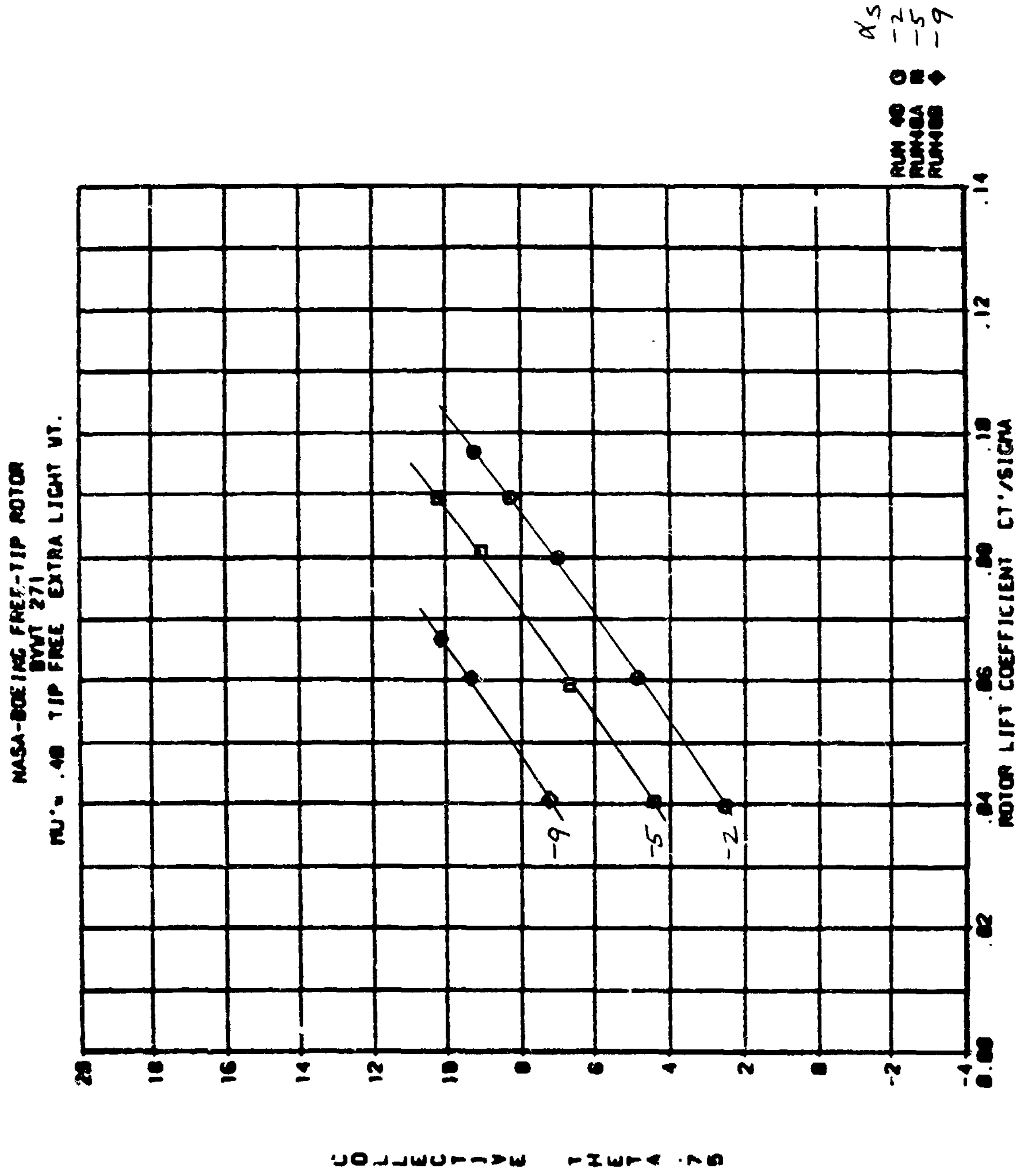
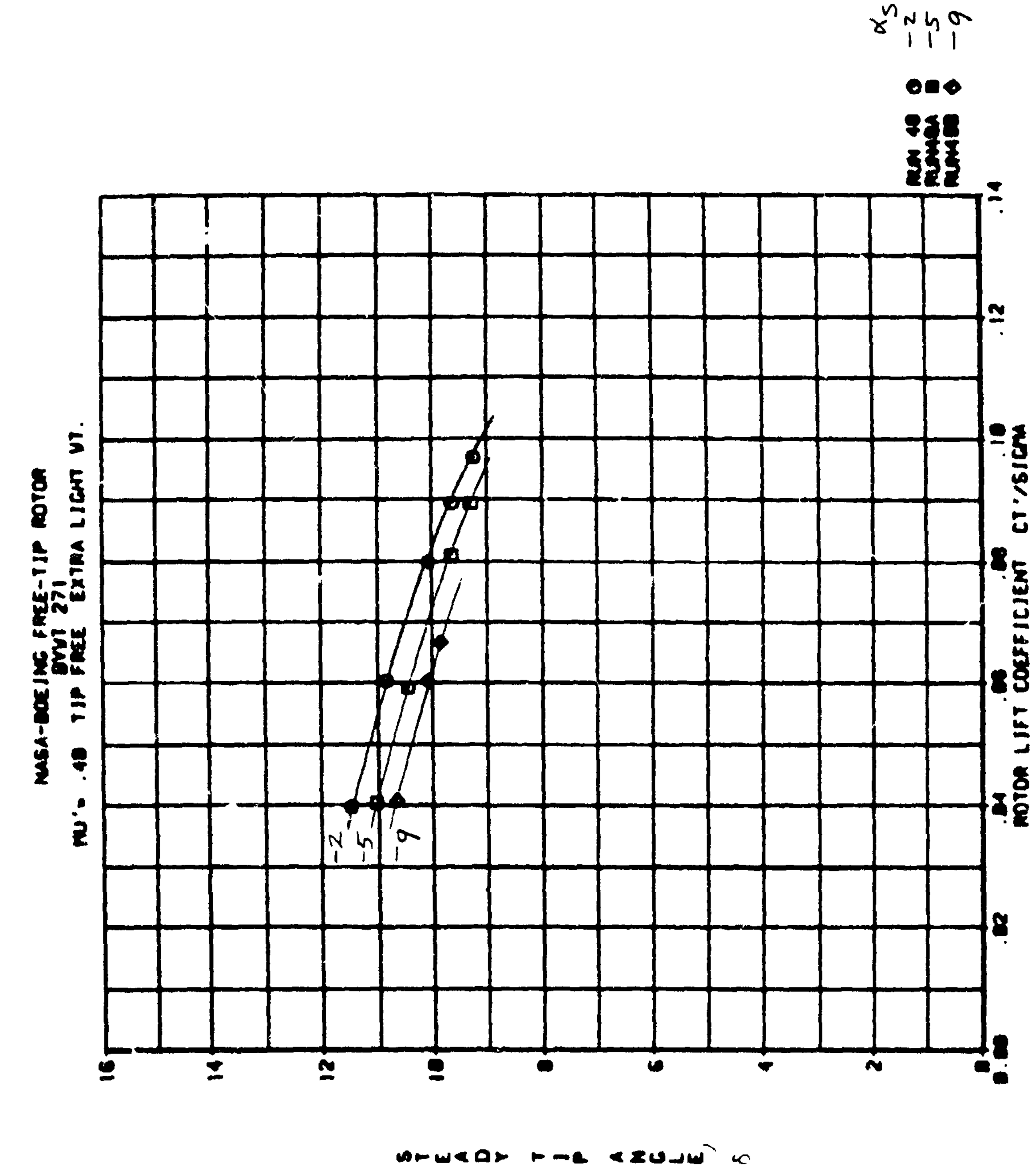
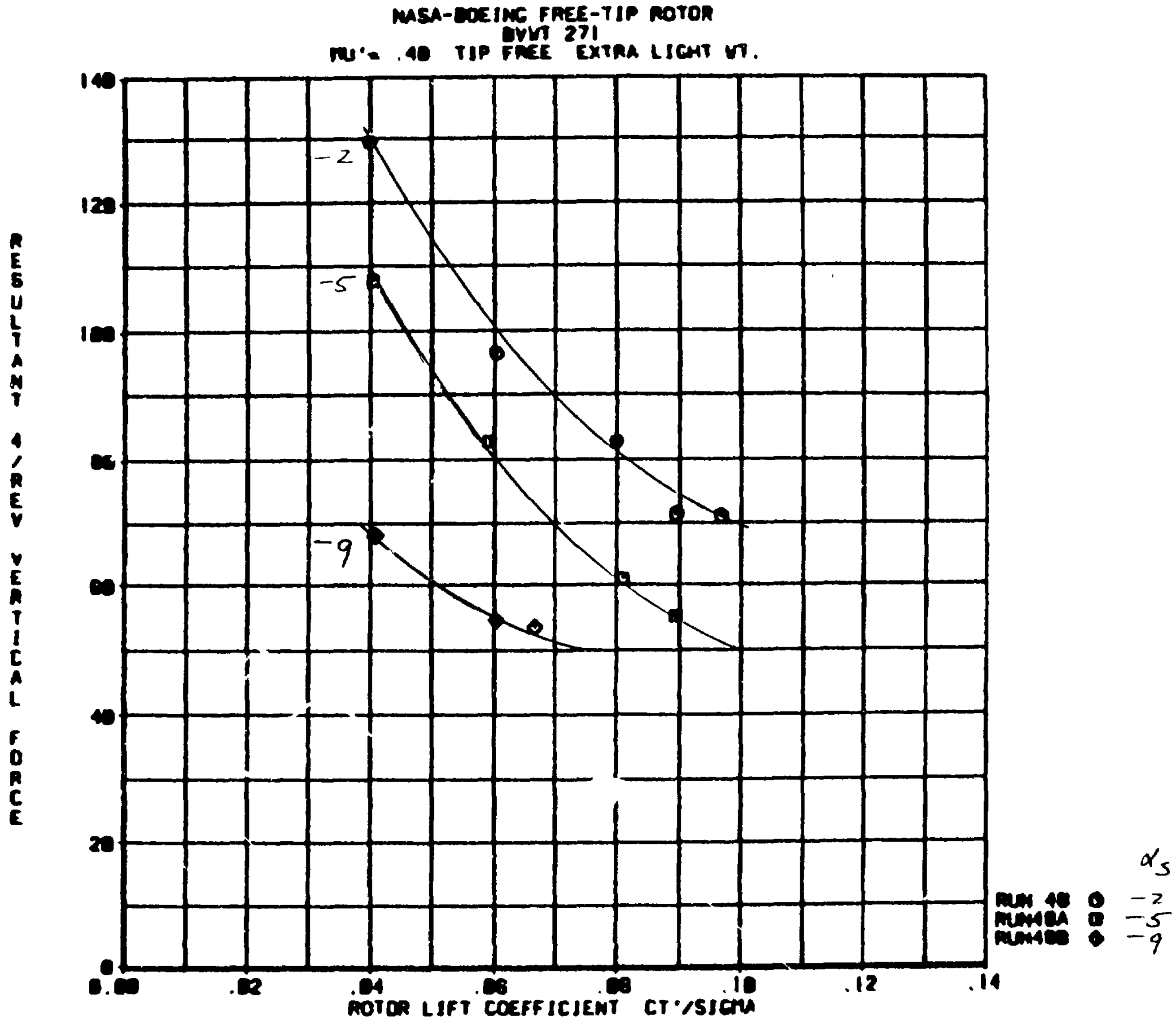



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .40 TIP FREE EXTRA LIGHT WT.
RUN 48
RUN48A
RUN48B
αs
-2
-5
-9
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
STEADY TIP ANGLE, δ
0
2
4
6
8
10
12
14
16



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .40 TIP FREE EXTRA LIGHT WT.
RESULTANT 4/REV VERTICAL FORCE
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
20
40
60
80
100
120
140
-2
-5
-9
α_s
RUN 48 -2
RUN48A -5
RUN48B -9

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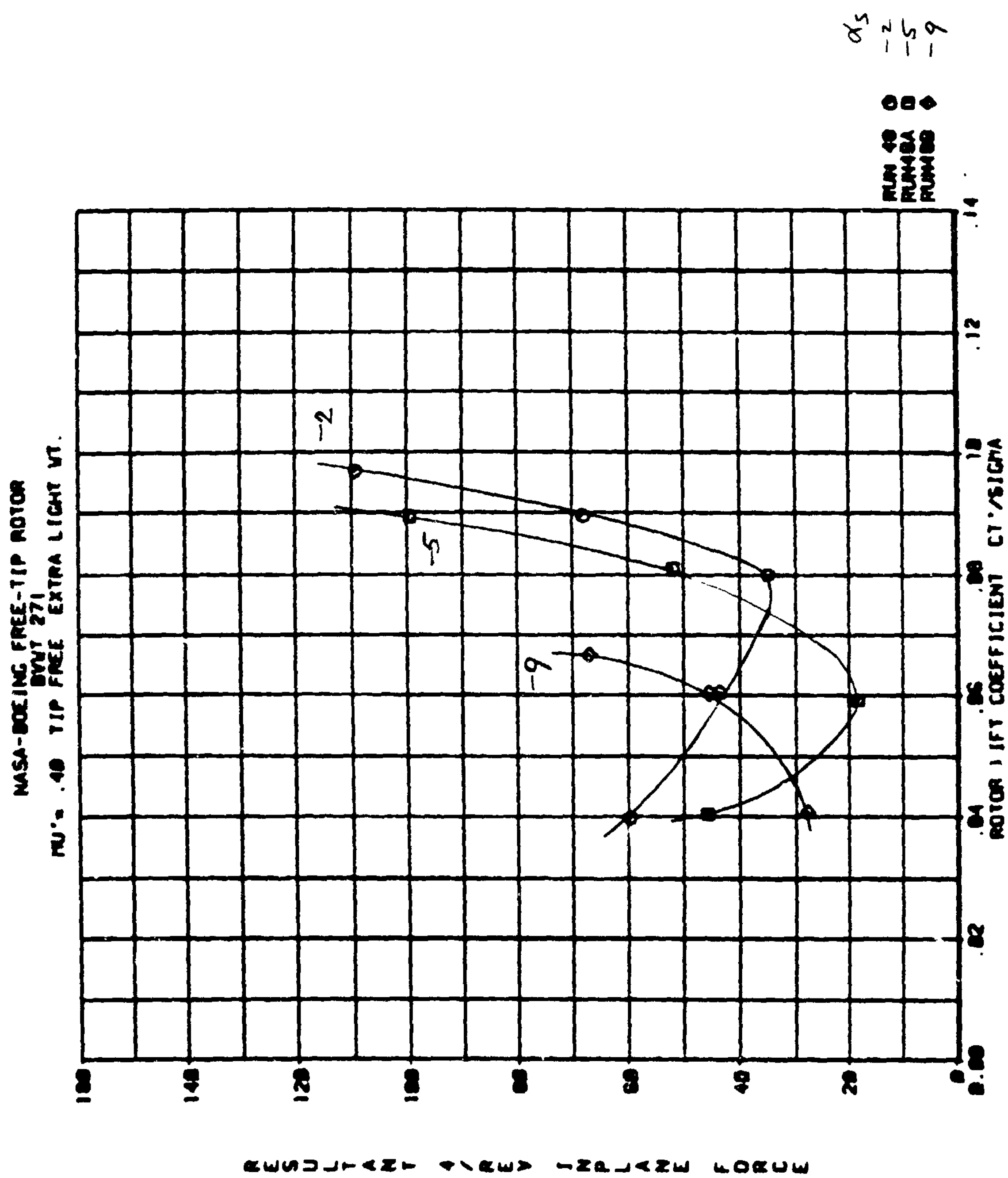
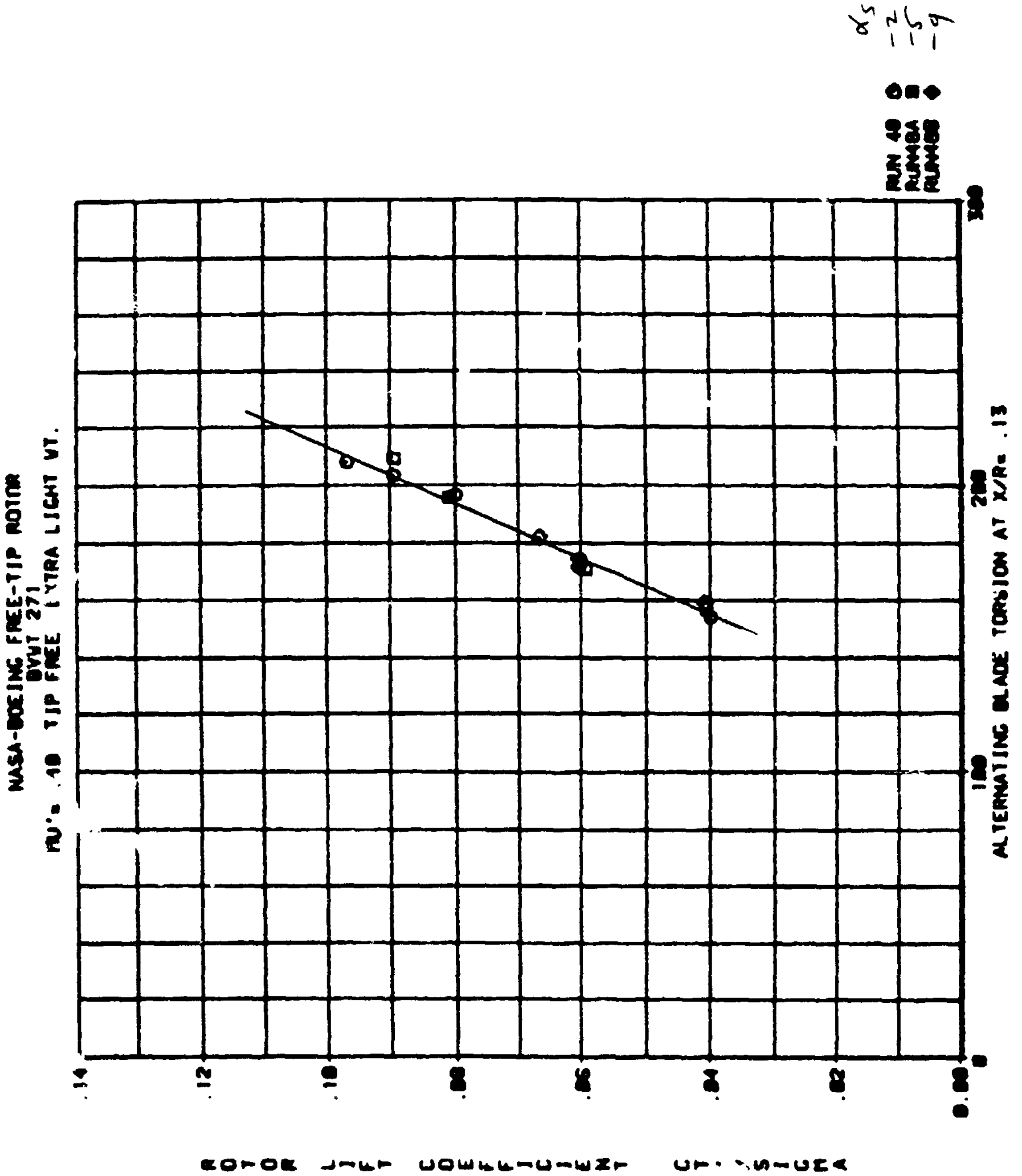
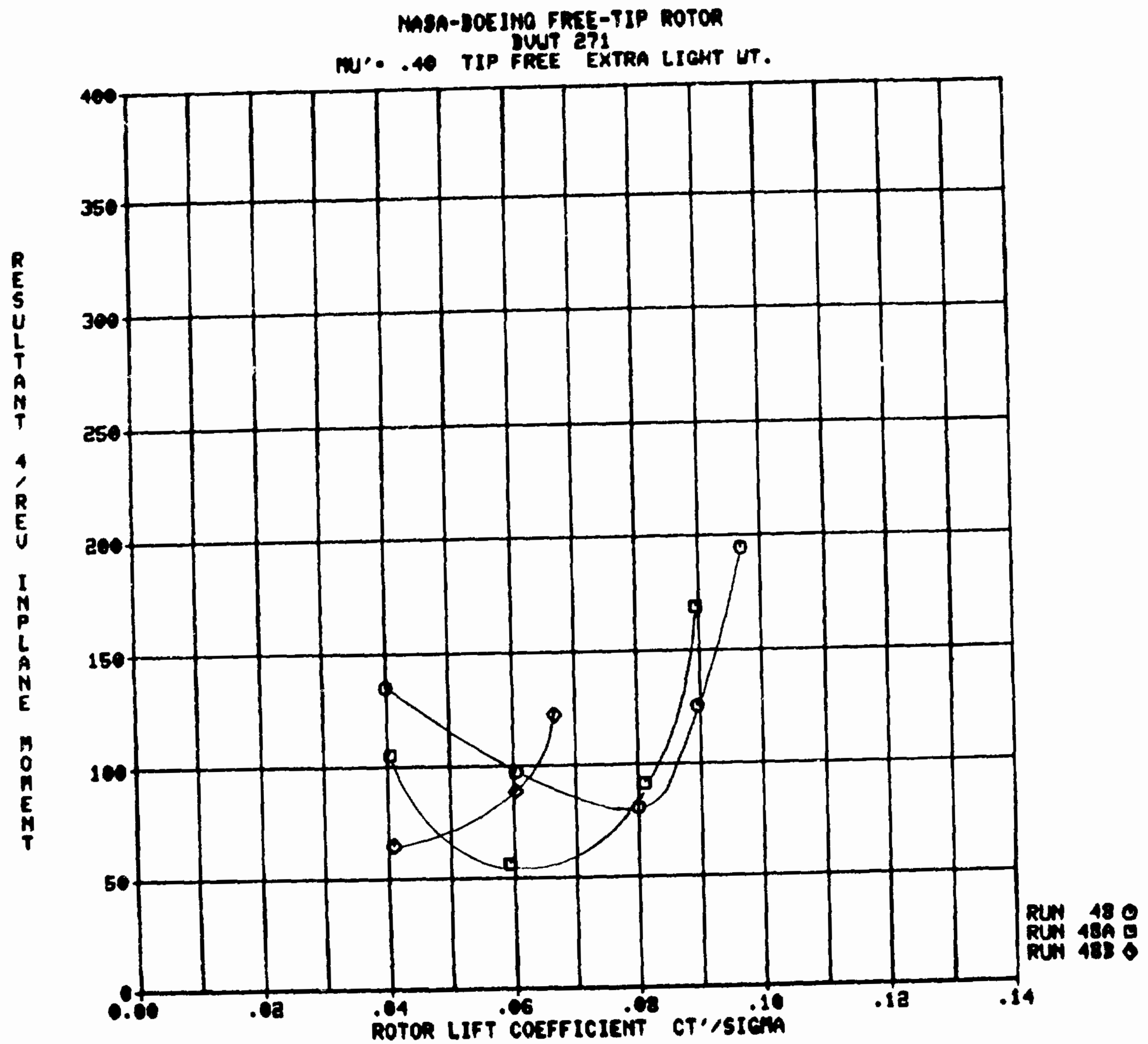
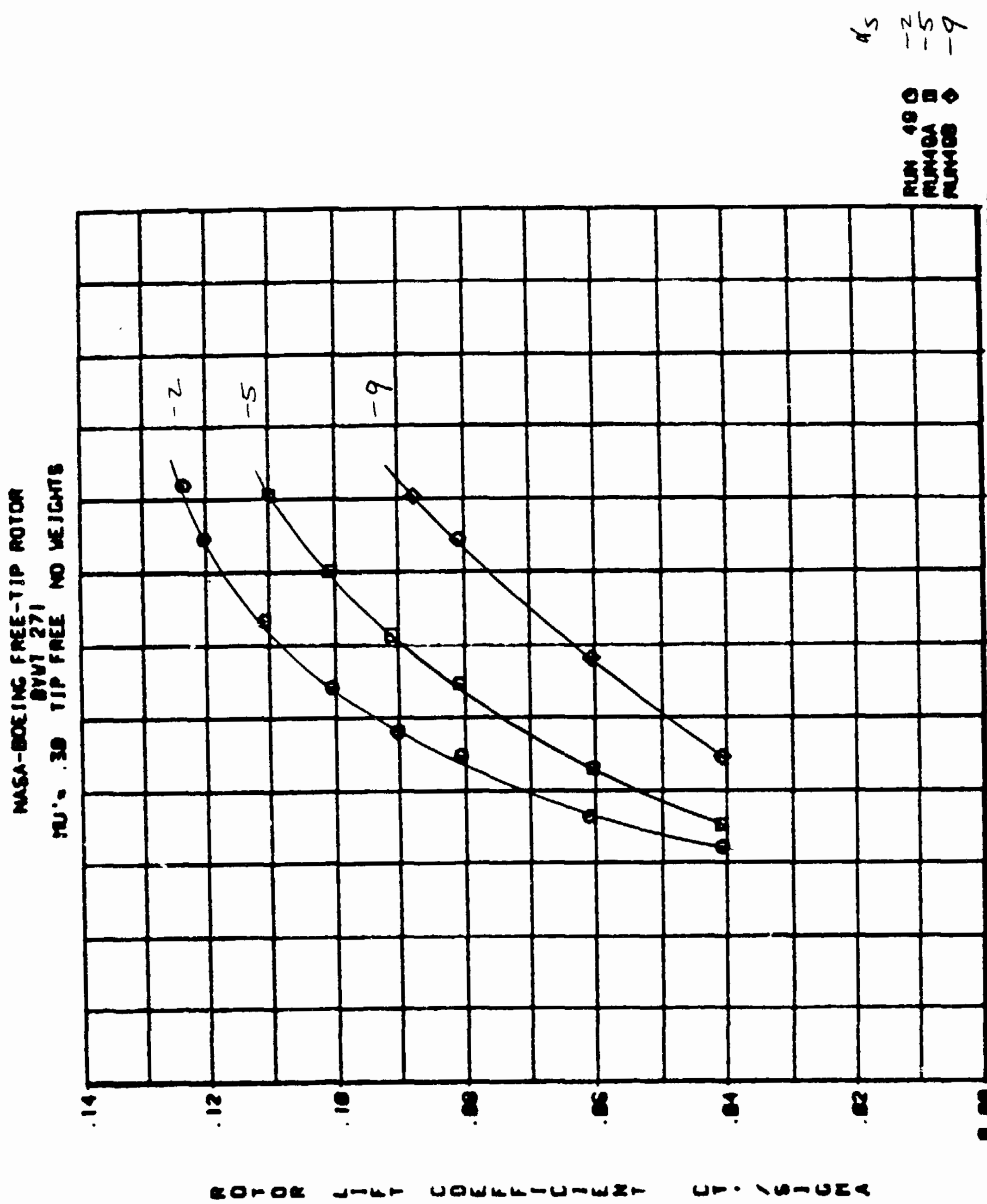
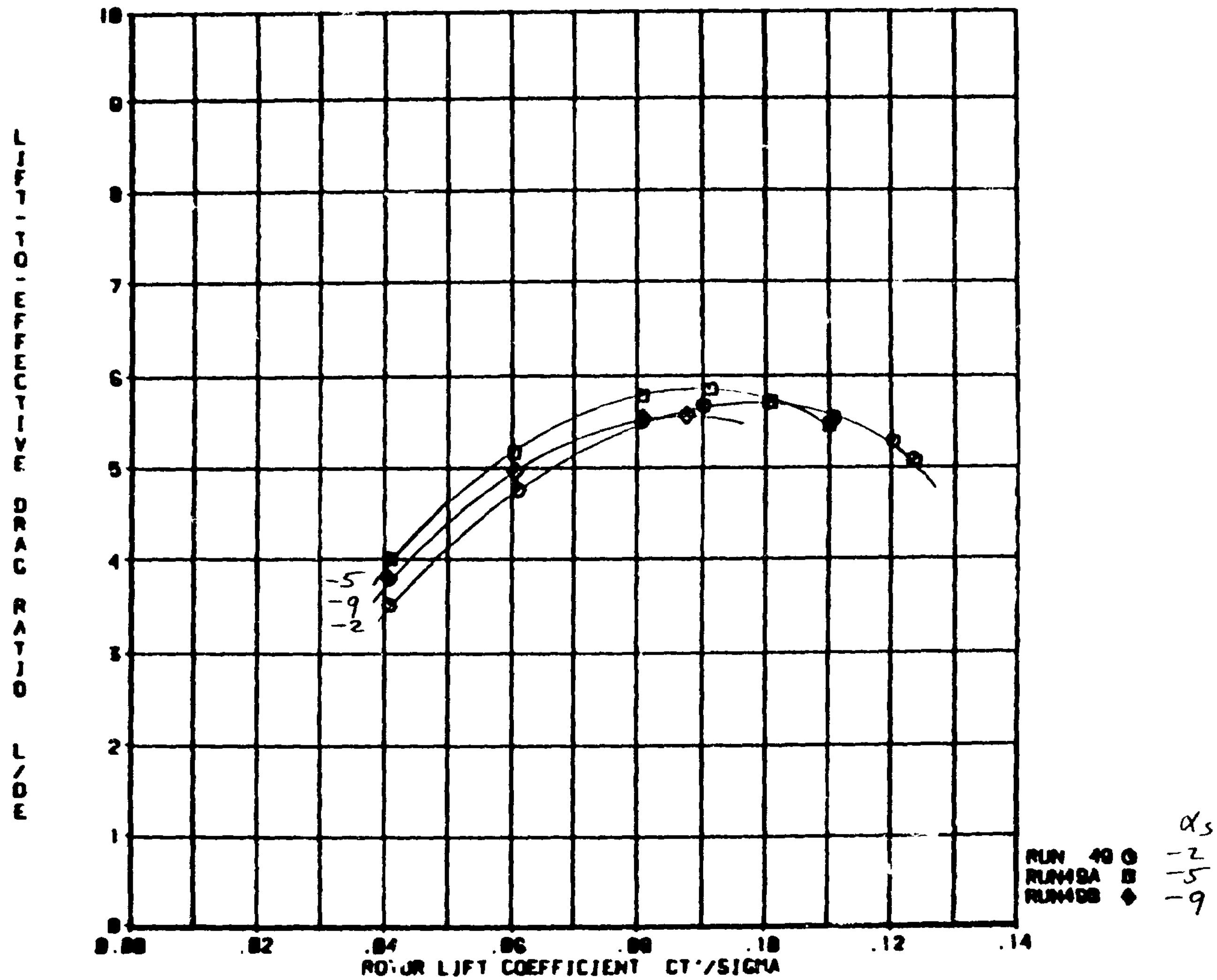



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .18 TIP FREE EXTRA LIGHT WT.
ALTERNATING BLADE TORSION AT X/R= .13
RUN 40
0
100
200
300
.14
.12
.10
.08
.06
.04
.02
0.00


NASA-BOEING FREE-TIP ROTOR
DWUT 271
MU'= .40 TIP FREE EXTRA LIGHT WT.
RESULTANT 4/REV INPLANE MOMENT
0
50
100
150
200
250
300
350
400
0.00
.02
.04
.06
.08
.10
.12
.14
ROTOR LIFT COEFFICIENT CT'/SIGMA
RUN 48
RUN 48A
RUN 48B


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .30 TIP FREE NO WEIGHTS
RUN 49
RUN49A
RUN49B
α_s
-2
-5
-9
ROTOR POWER COEFFICIENT CP/SIGMA
0.000
.002
.004
.006
.008
.010
.012
0.00
.02
.04
.06
.08
.10
.12
.14

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE NO WEIGHTS



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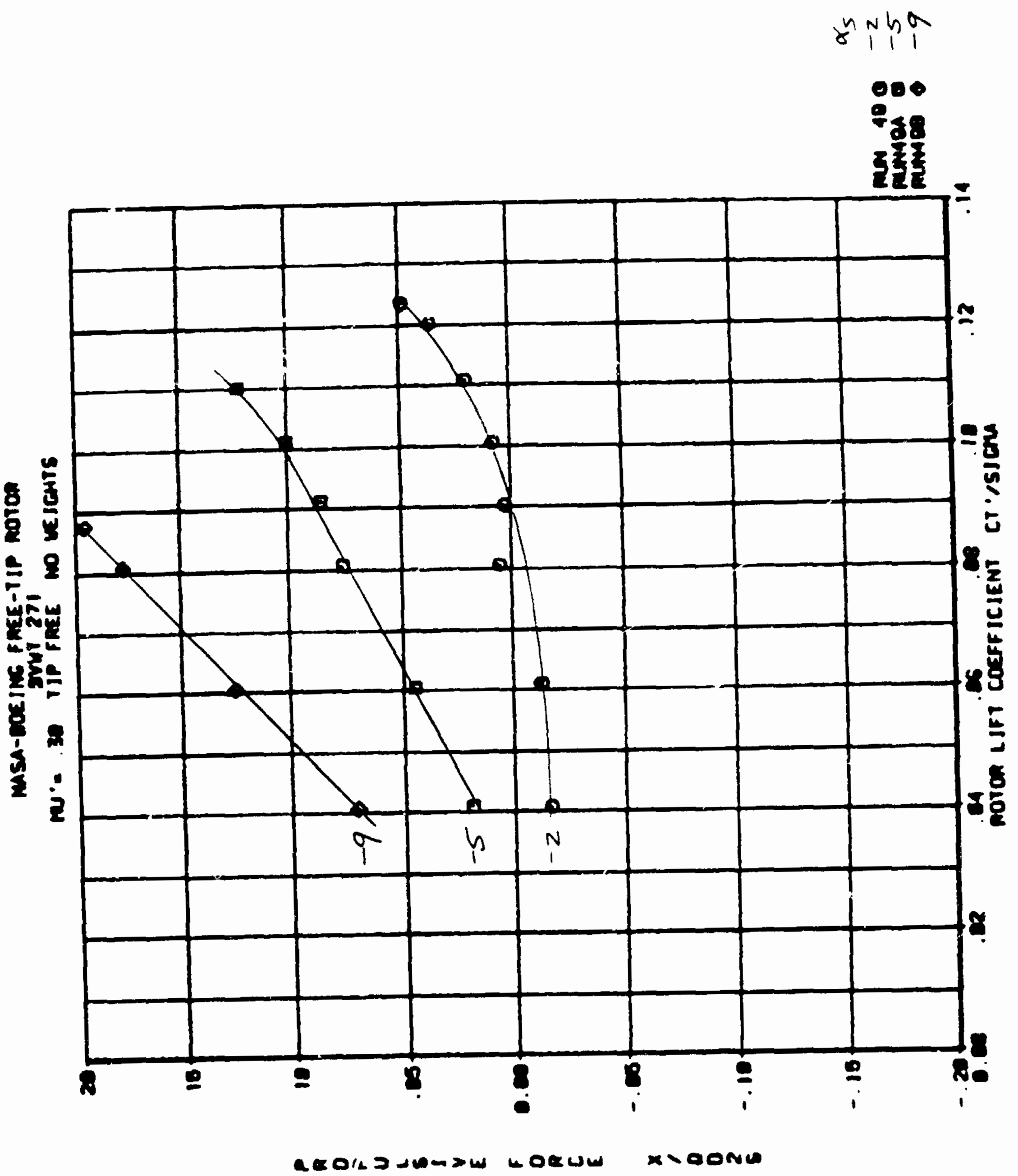

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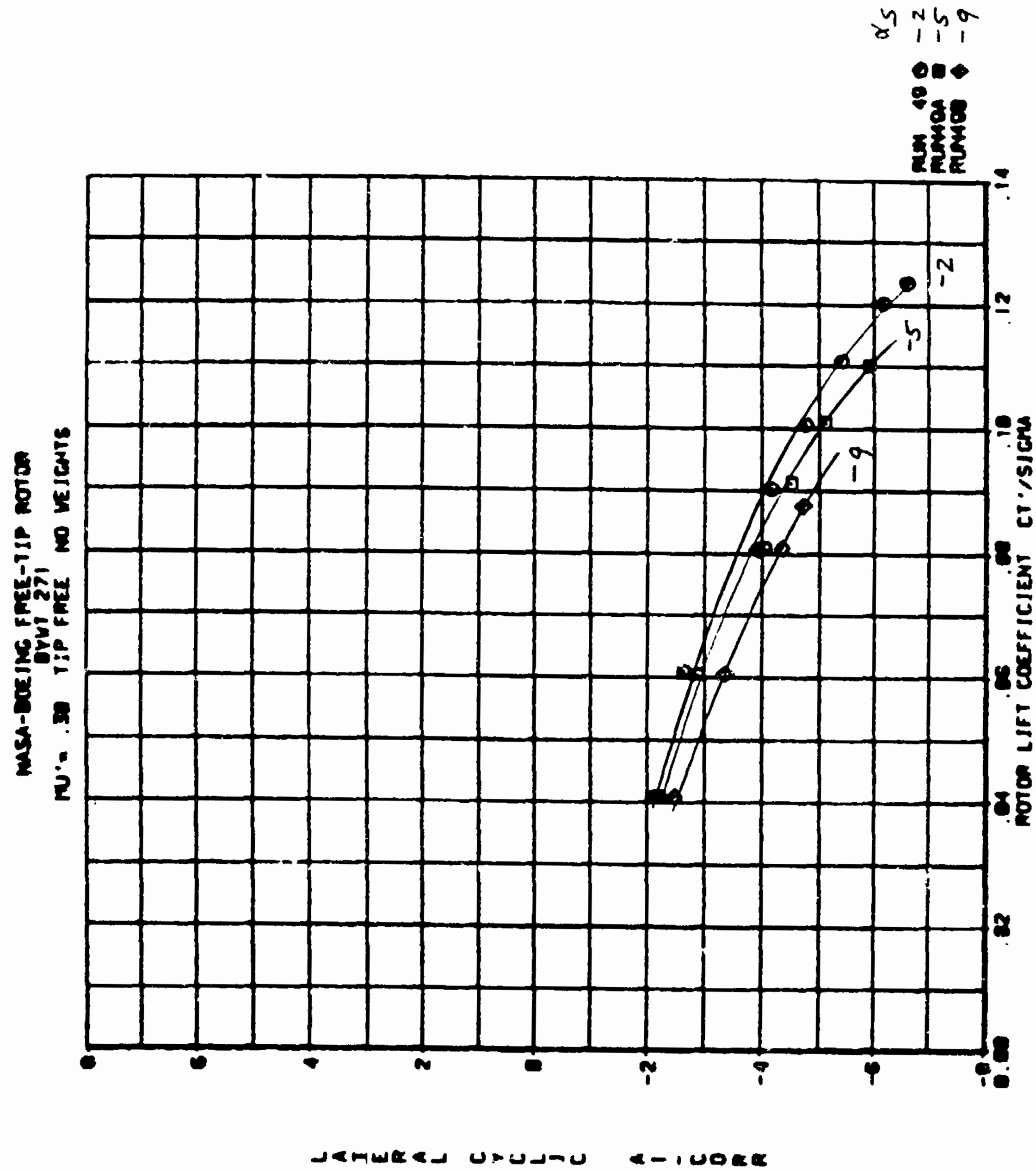
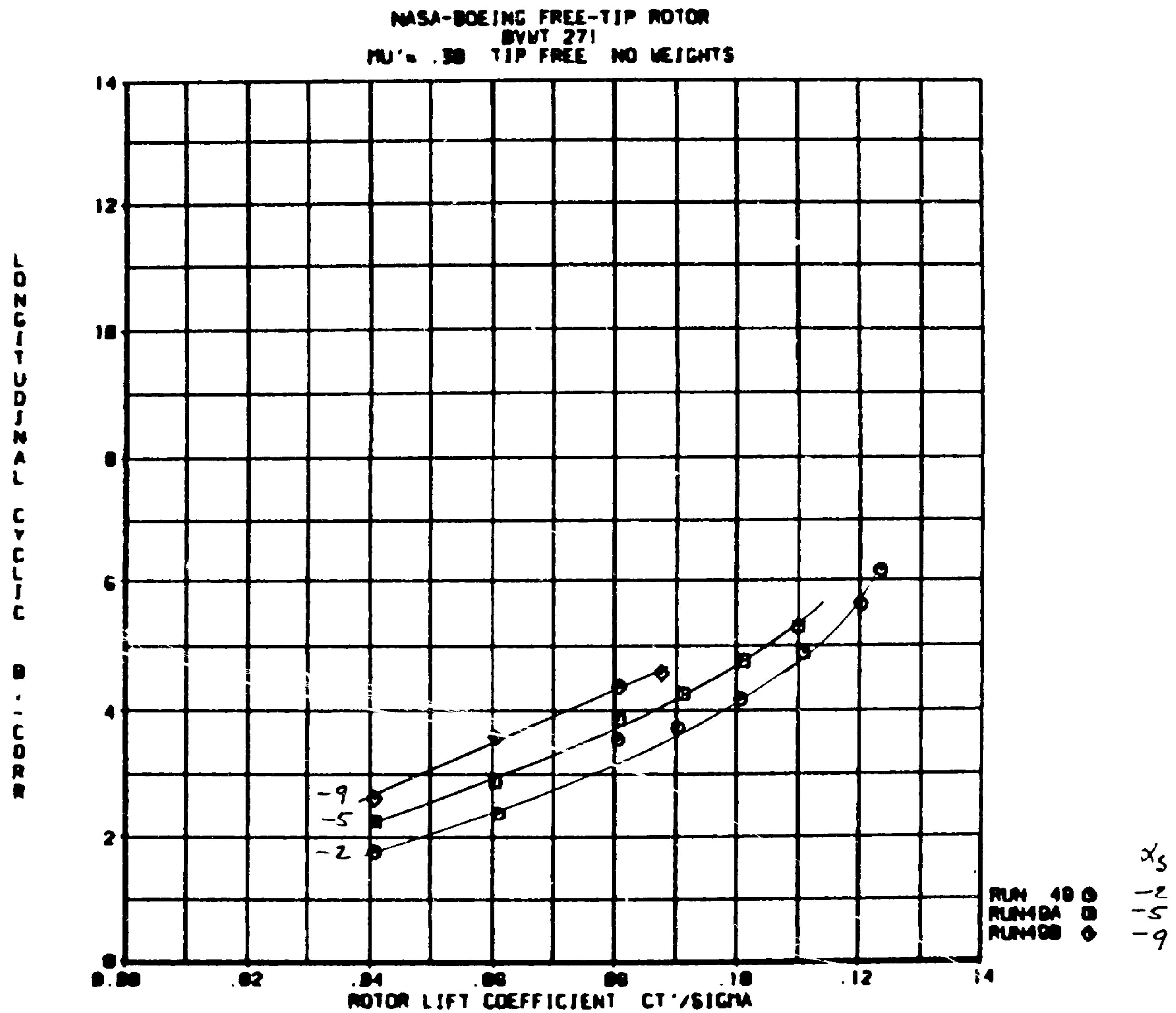
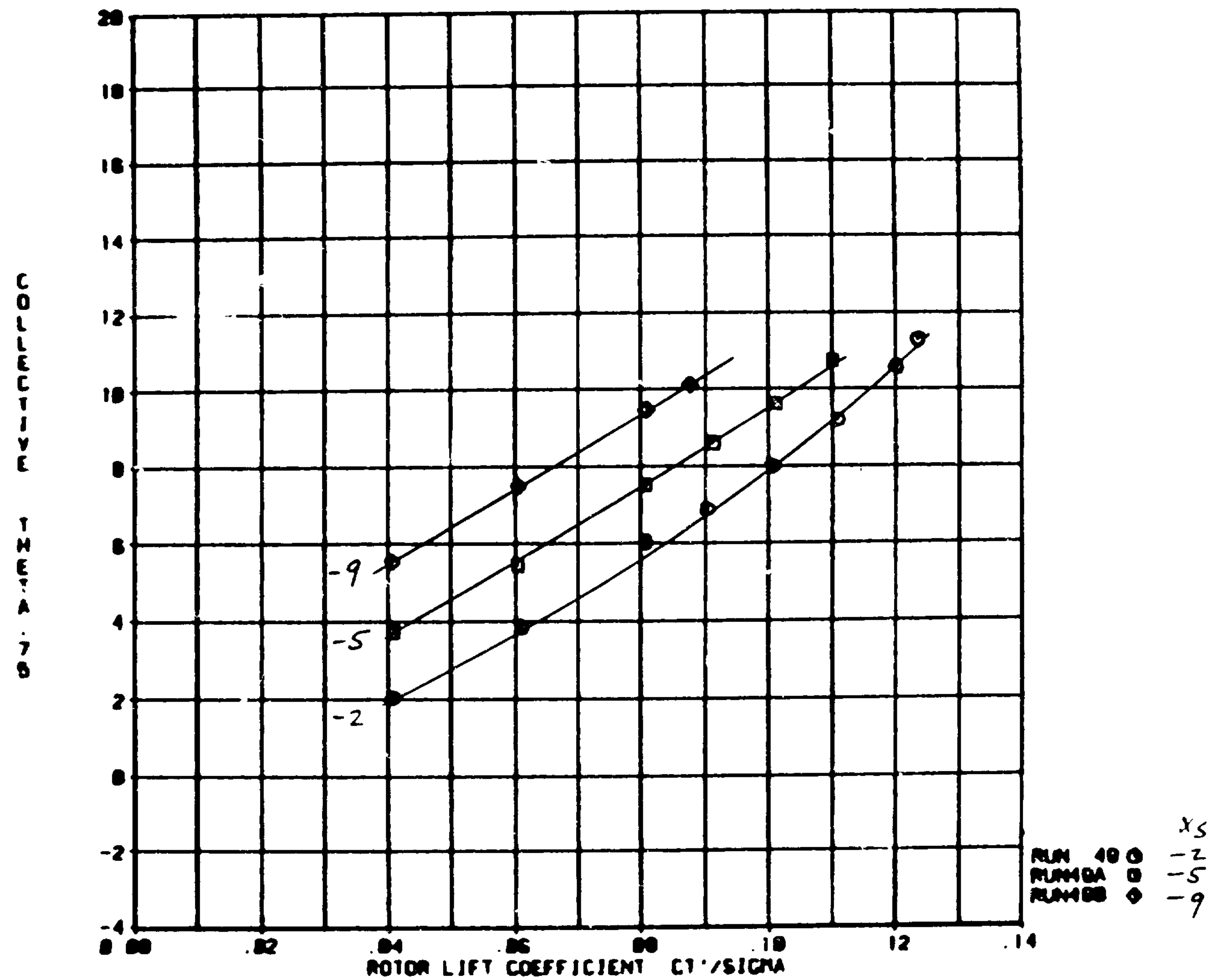
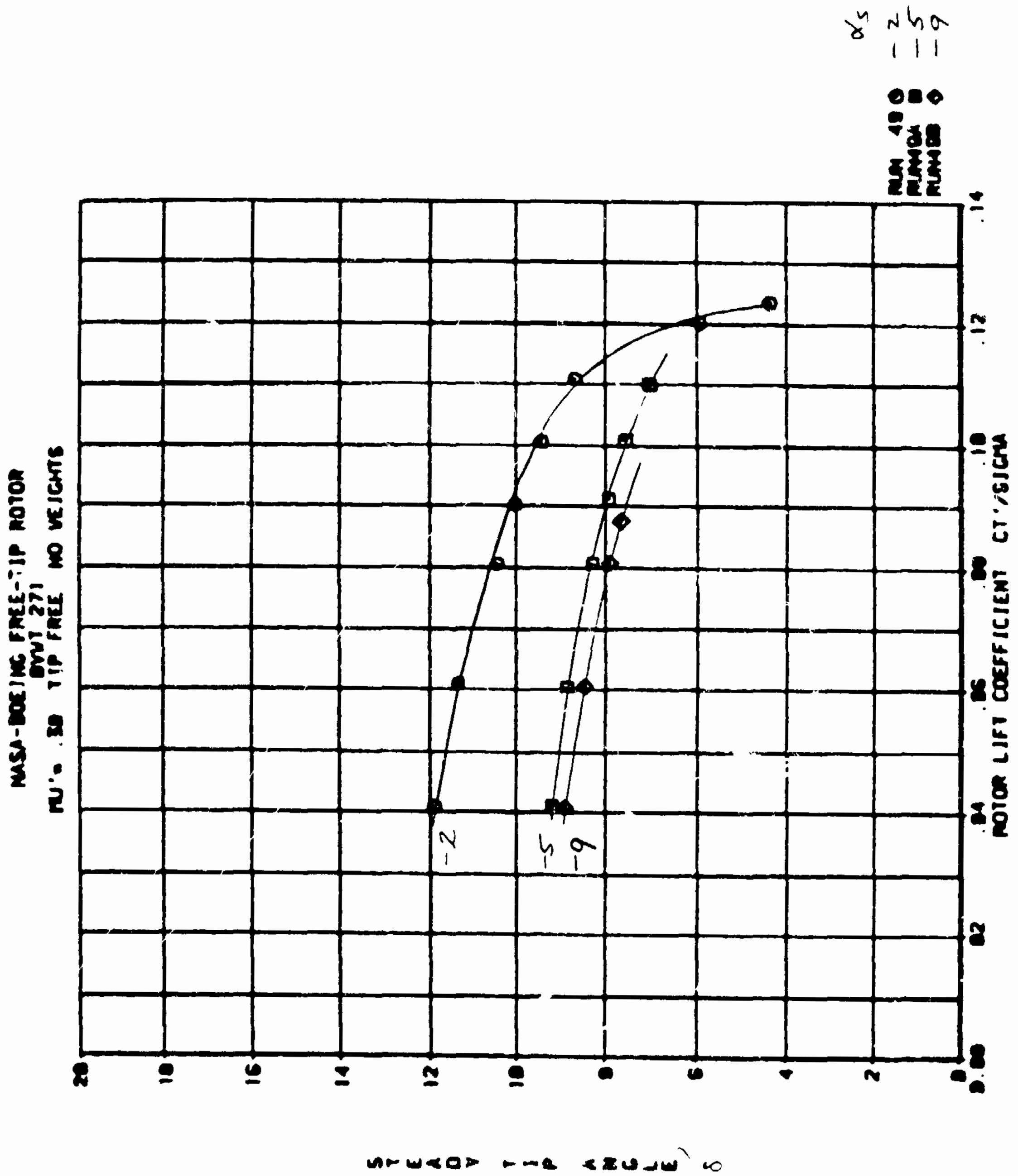




NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE NO WEIGHTS
LONGITUDINAL CYCLIC B1CORR
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
2
4
6
8
10
12
14
-9
-5
-2
α_s
RUN 40 ⊙ -2
RUN40A ⊡ -5
RUN40B ◇ -9

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE NO WEIGHTS




NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .30 TIP FREE NO WEIGHTS
ROTOR LIFT COEFFICIENT CT/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
2
4
6
8
10
12
14
16
18
20
RUN 49
αs
-2
-5
-9

ORIGINAL PAGE IS
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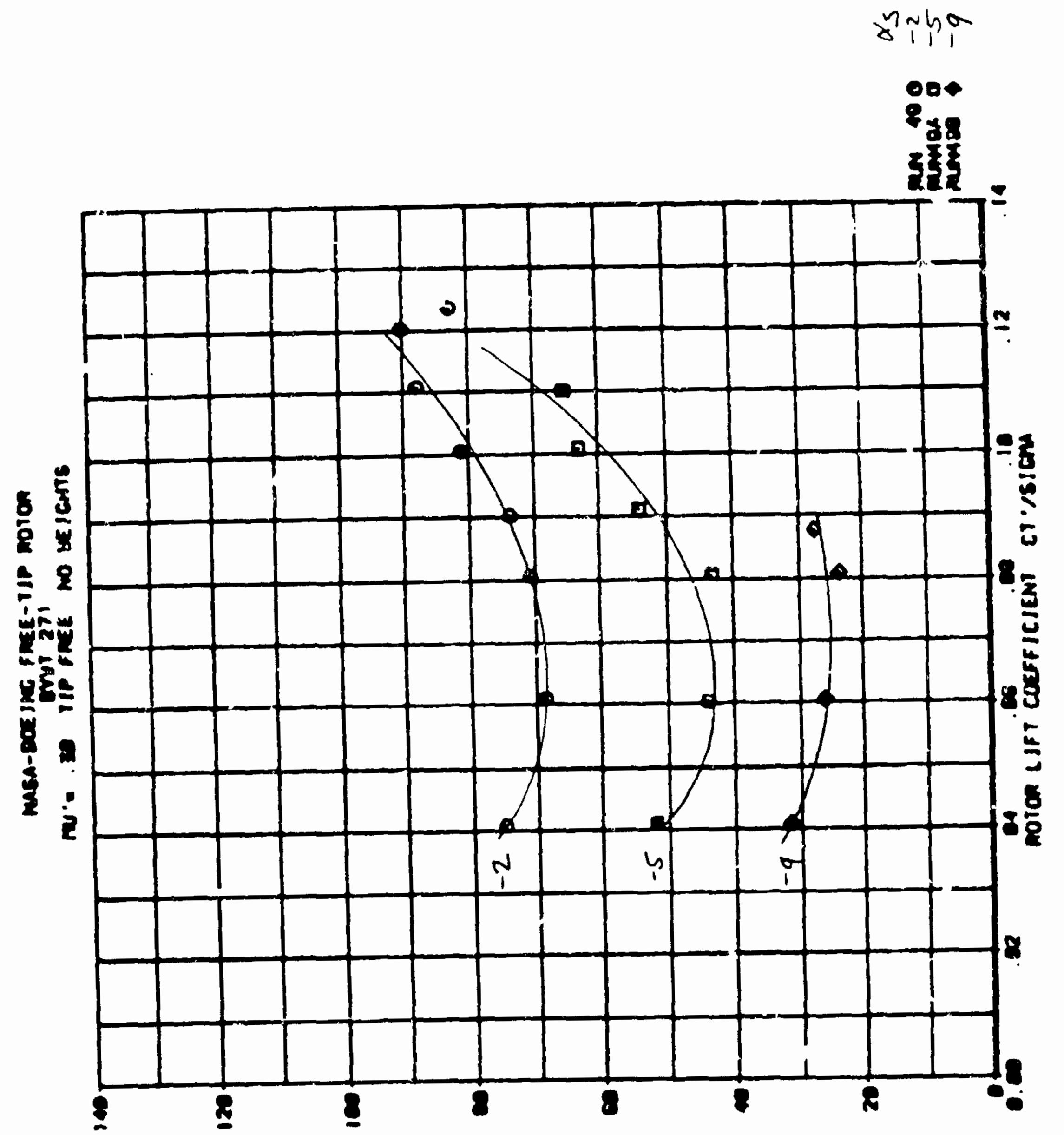
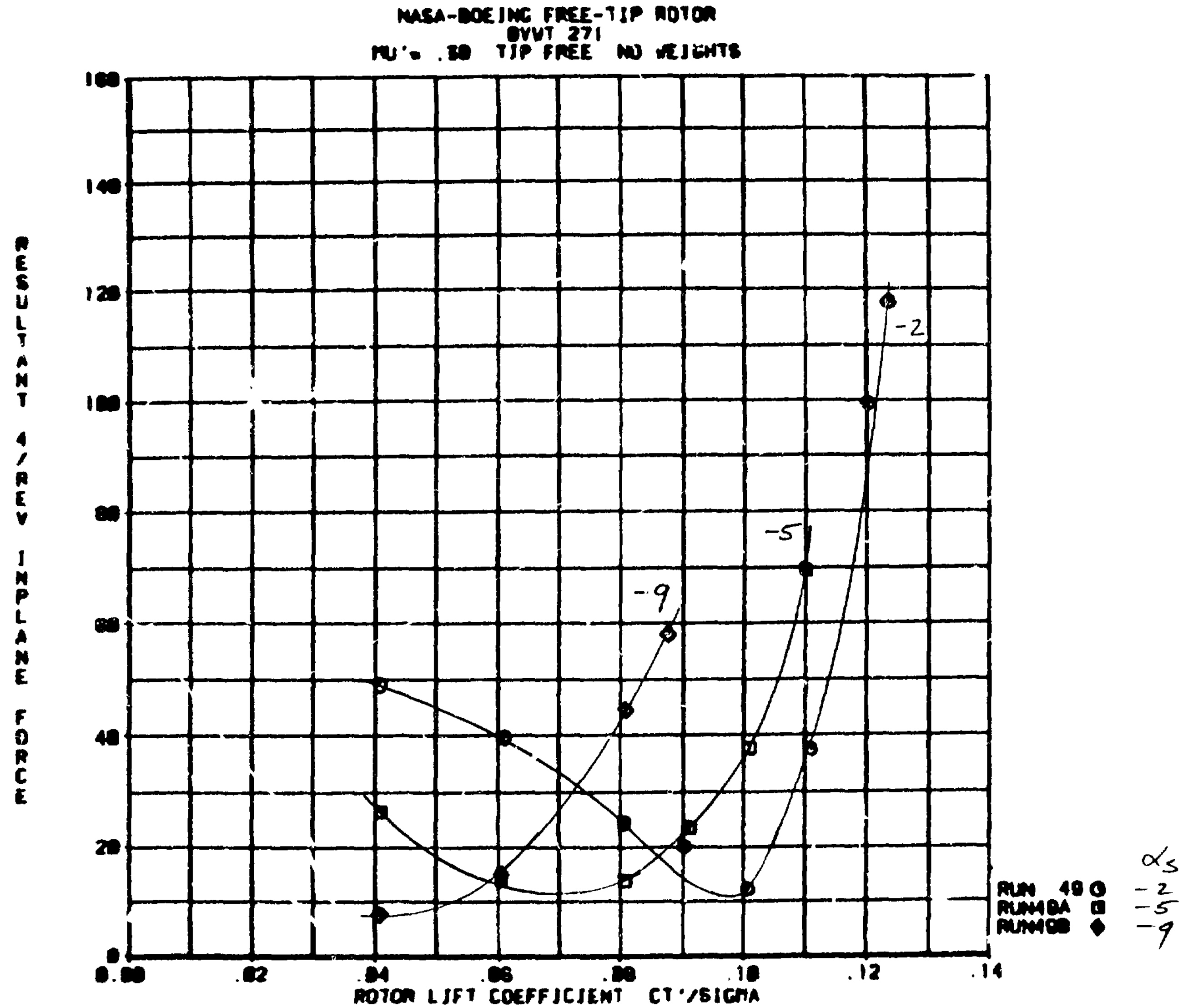
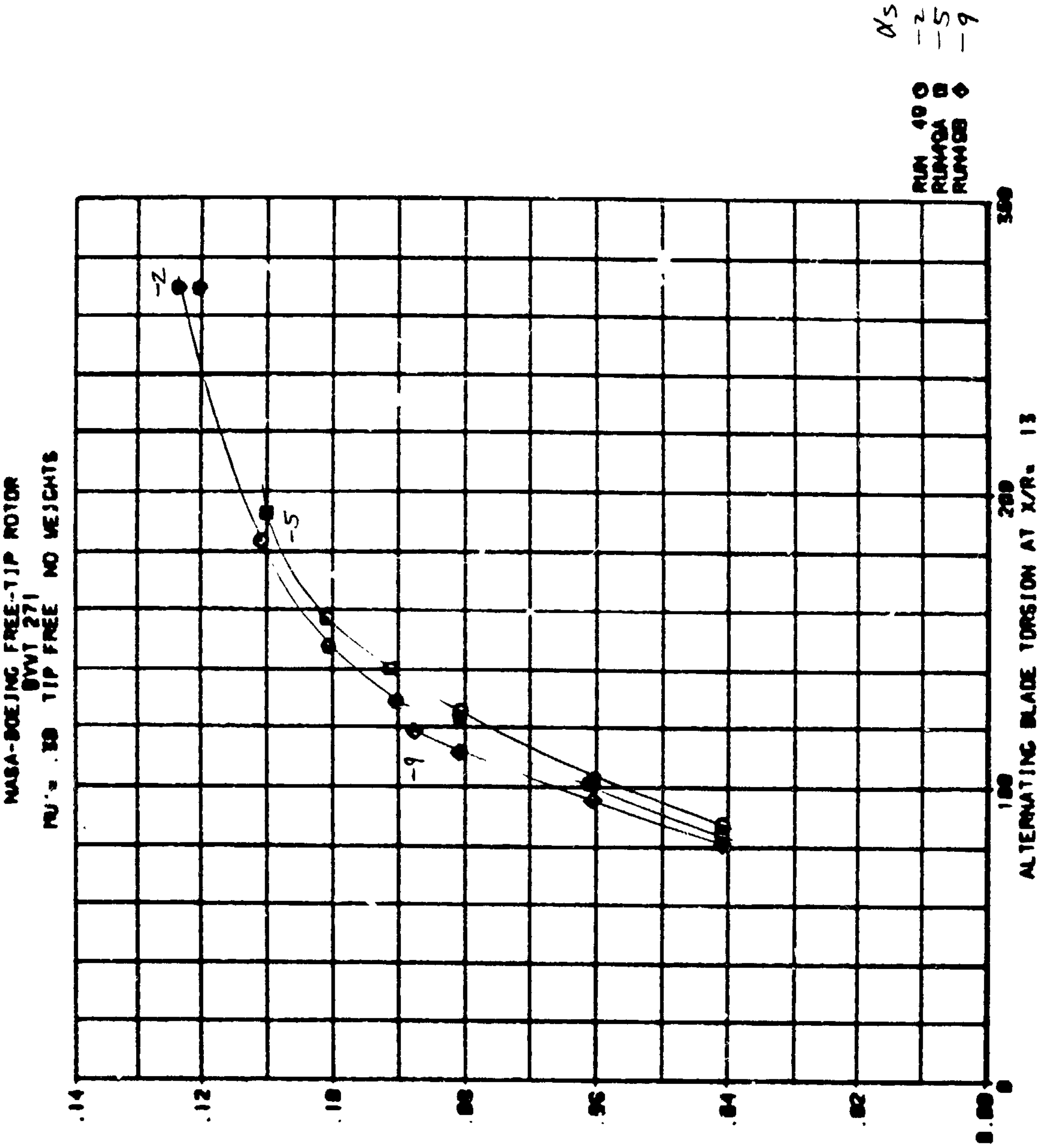
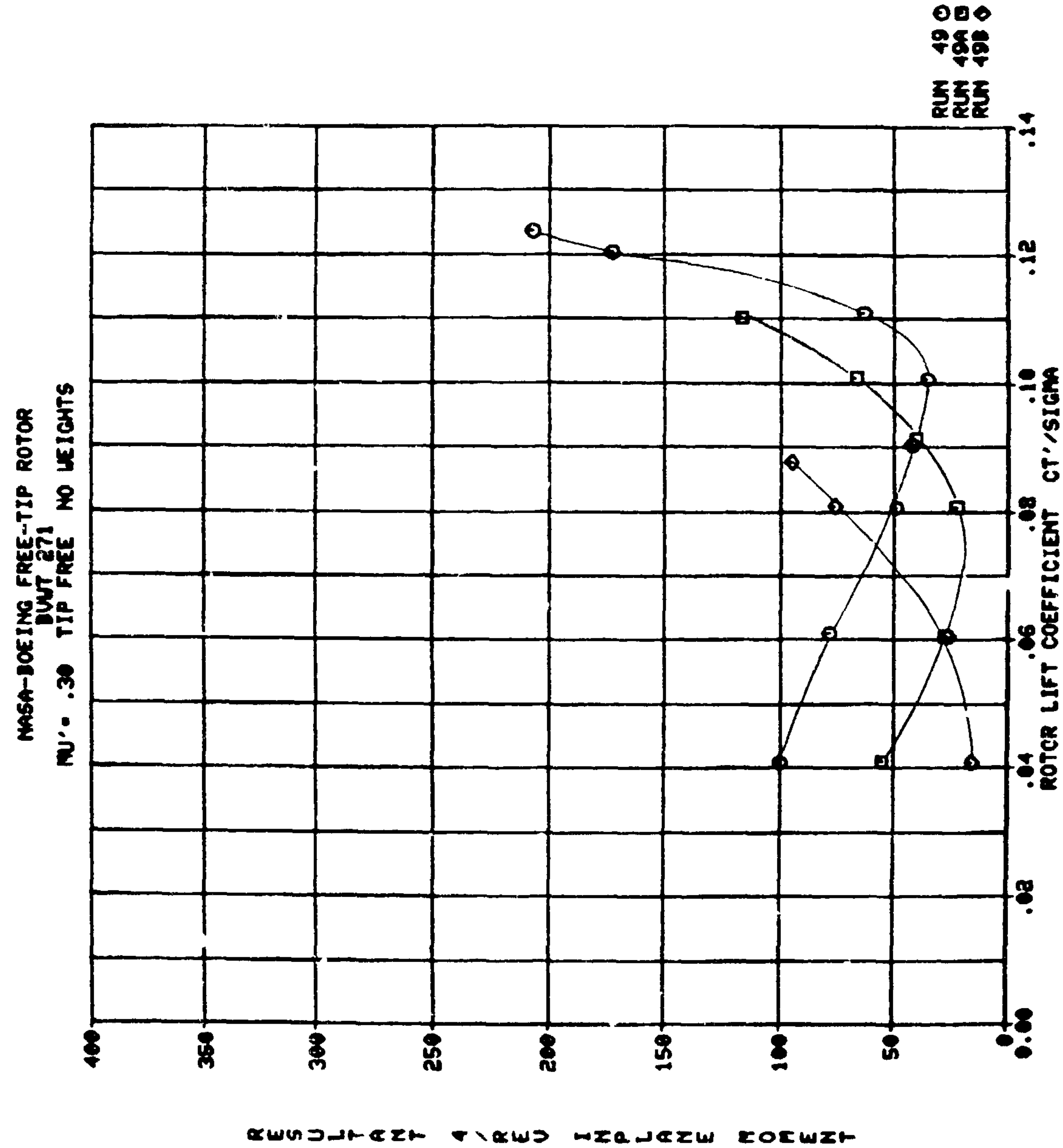
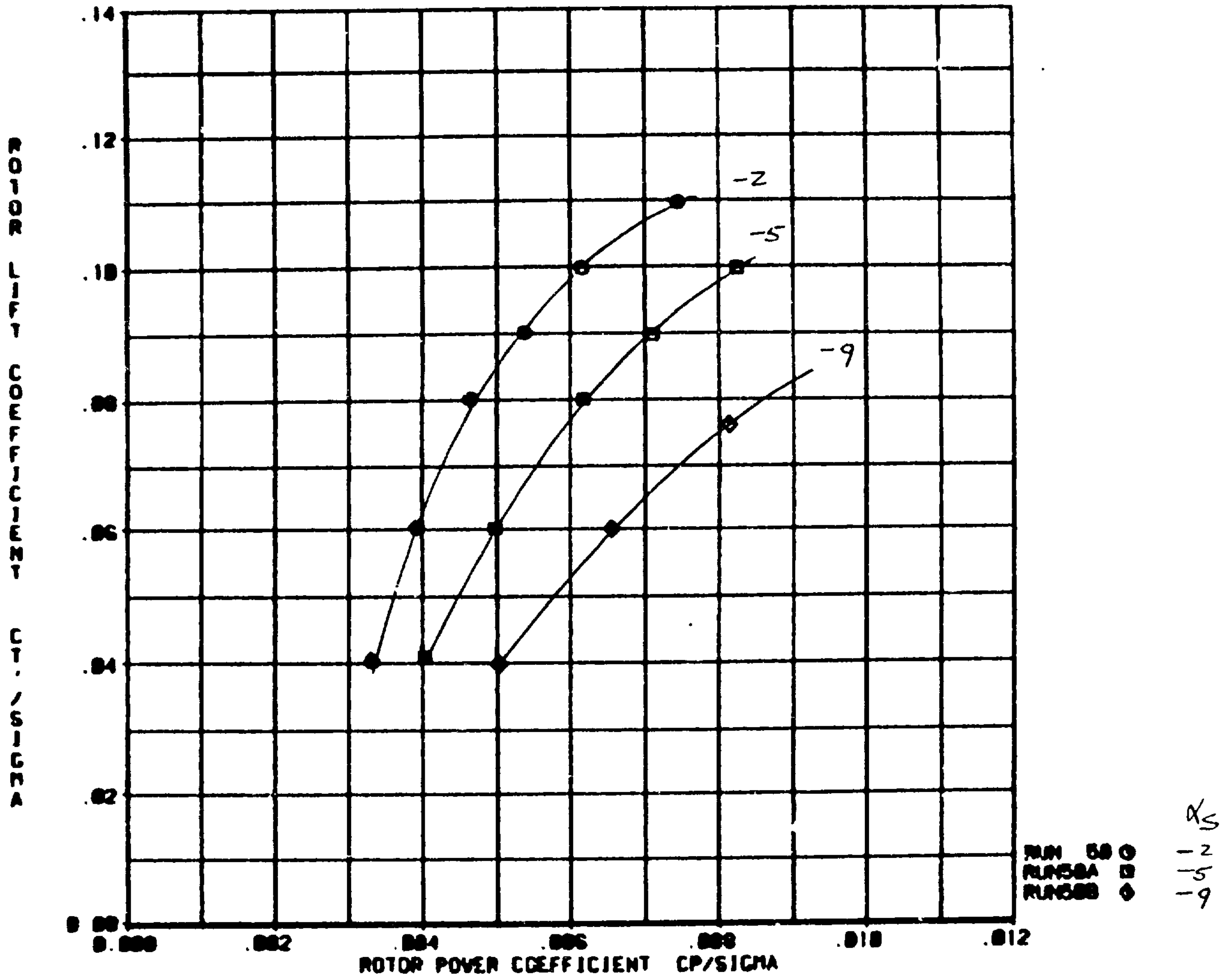


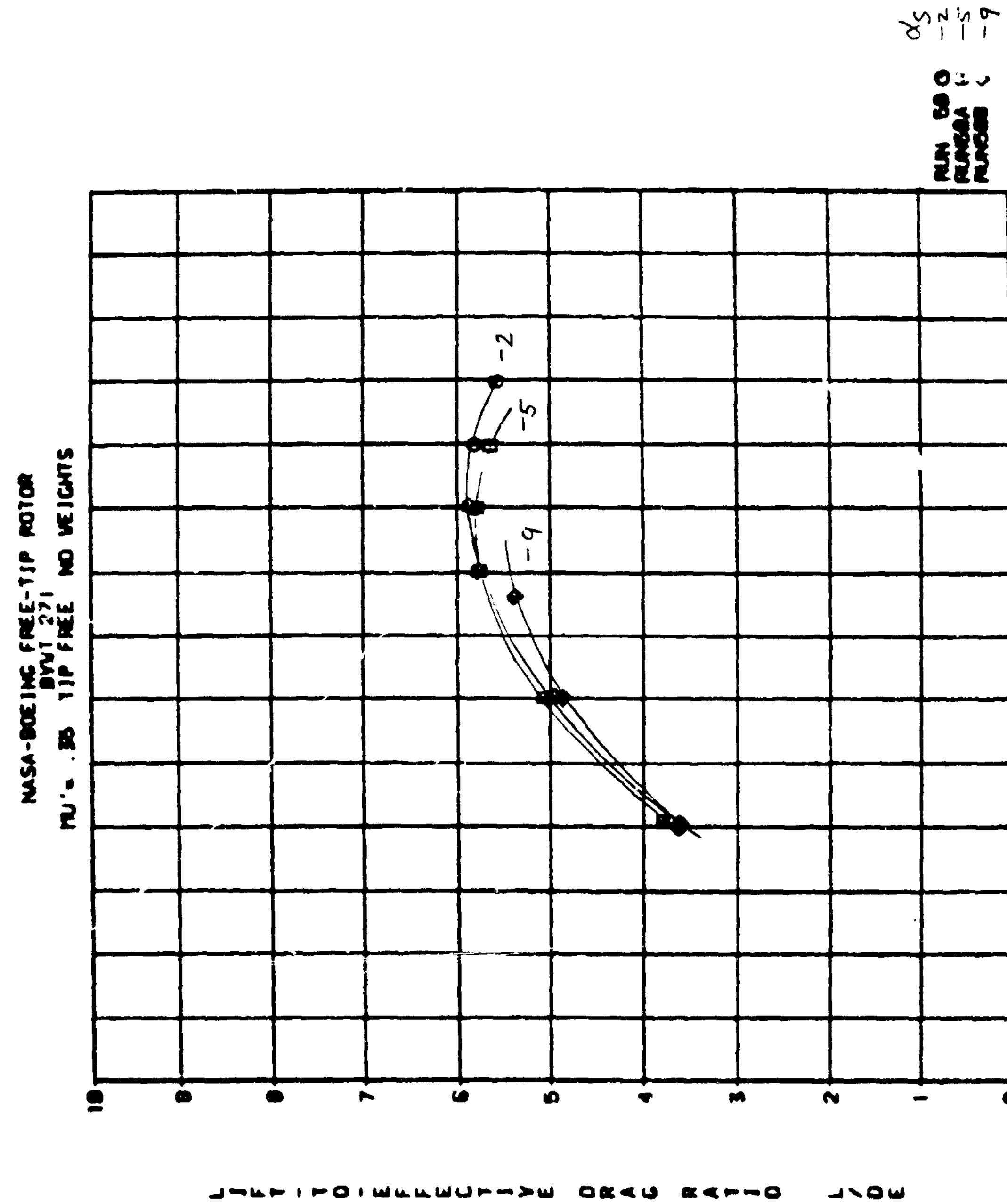

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .30 TIP FREE NO WEIGHTS
RESULTANT 4/REV INPLANE FORCE
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
20
40
60
80
100
120
140
160
-2
-5
-9
α_s
RUN 49
RUN49A
RUN49B
-2
-5
-9

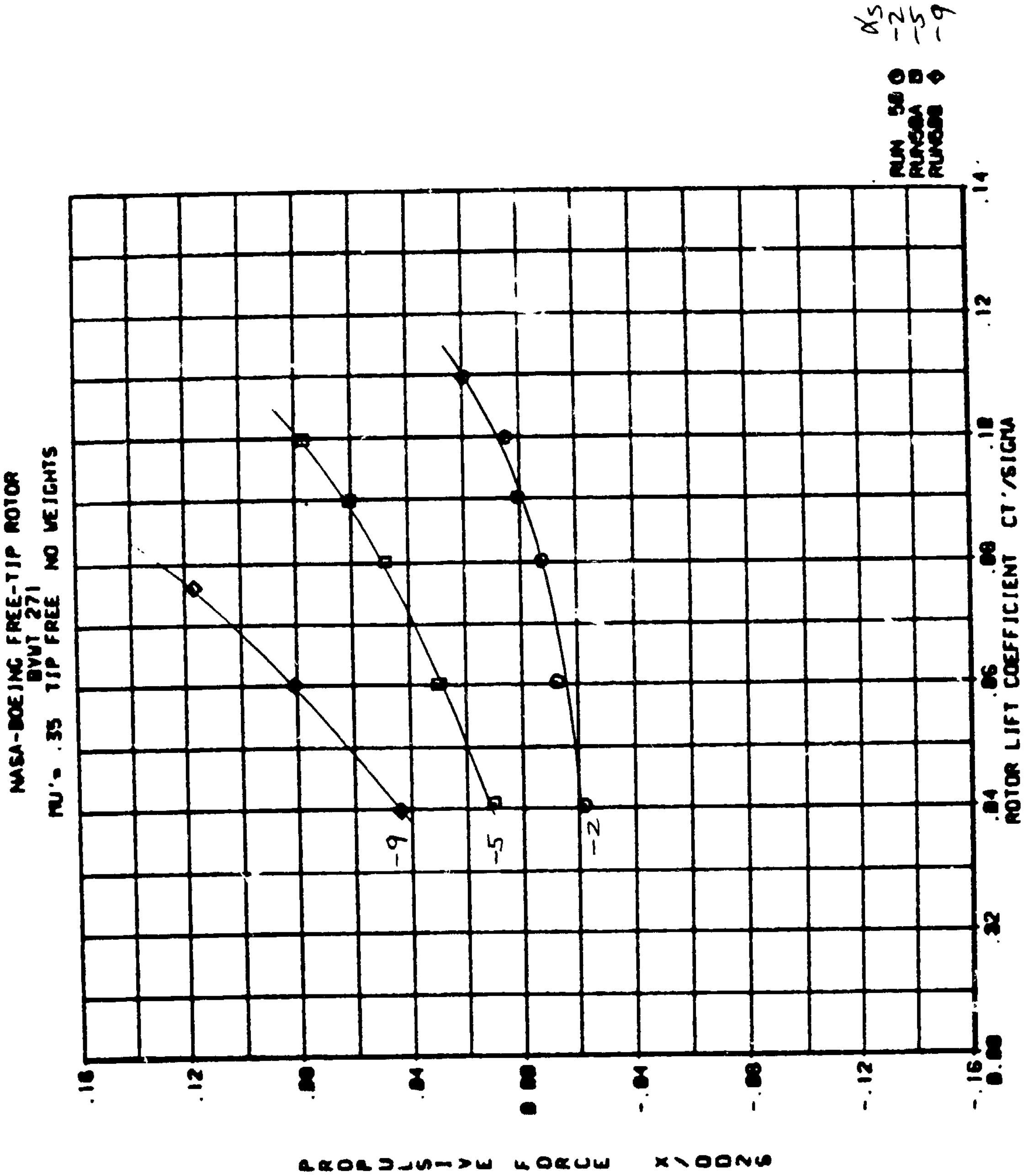

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .30 TIP FREE NO WEIGHTS
RUN 40 O
RUN40A □
RUN40B ◇
α_s -2 -5 -9
ALTERNATING BLADE TORSION AT X/R= 13
0
100
200
300
0.00
.02
.04
.06
.08
.10
.12
.14

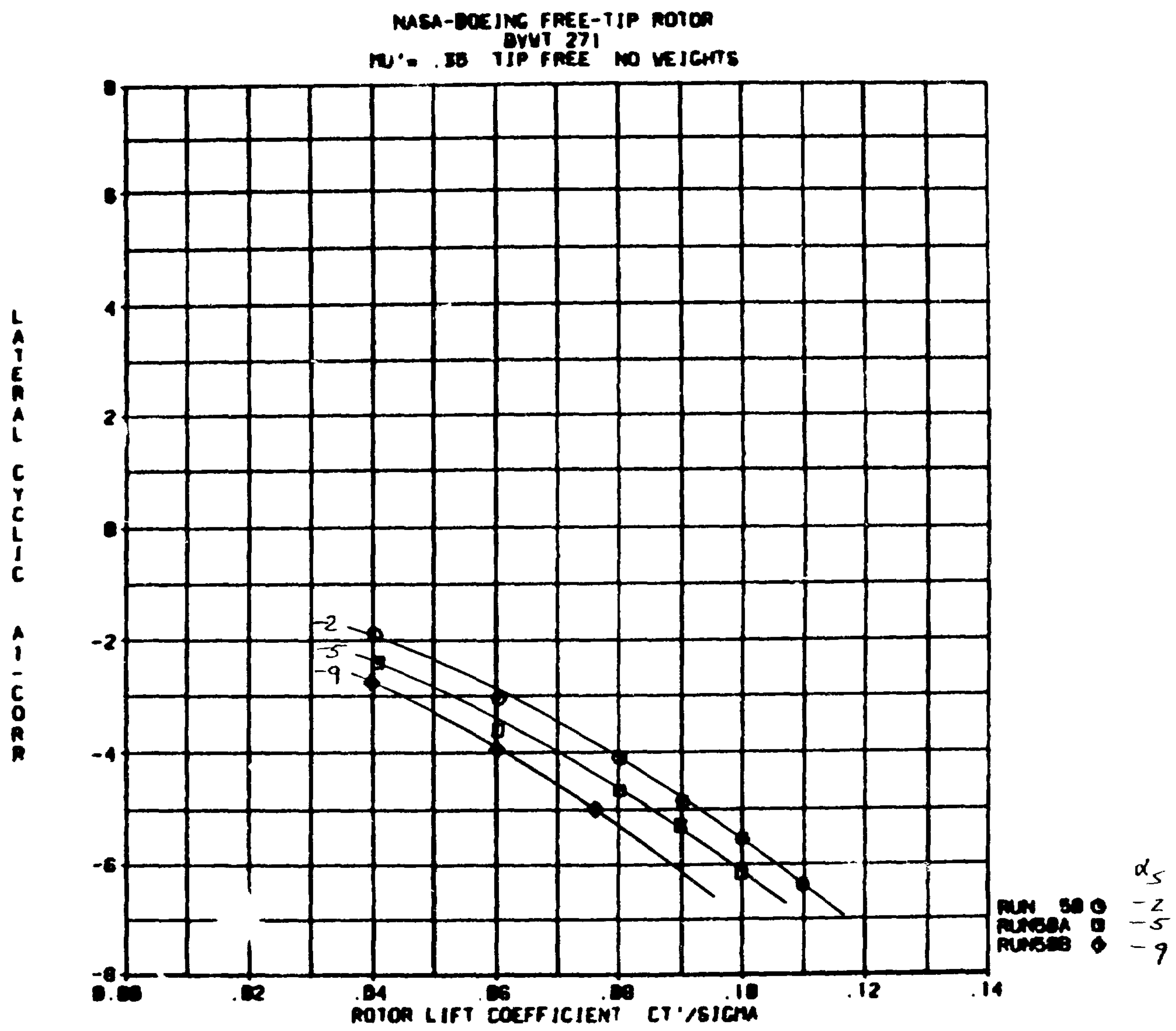

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .30 TIP FREE NO WEIGHTS
RUN 49
RUN 49A
RUN 49B
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
50
100
150
200
250
300
350
400

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .35 TIP FREE NO WEIGHTS

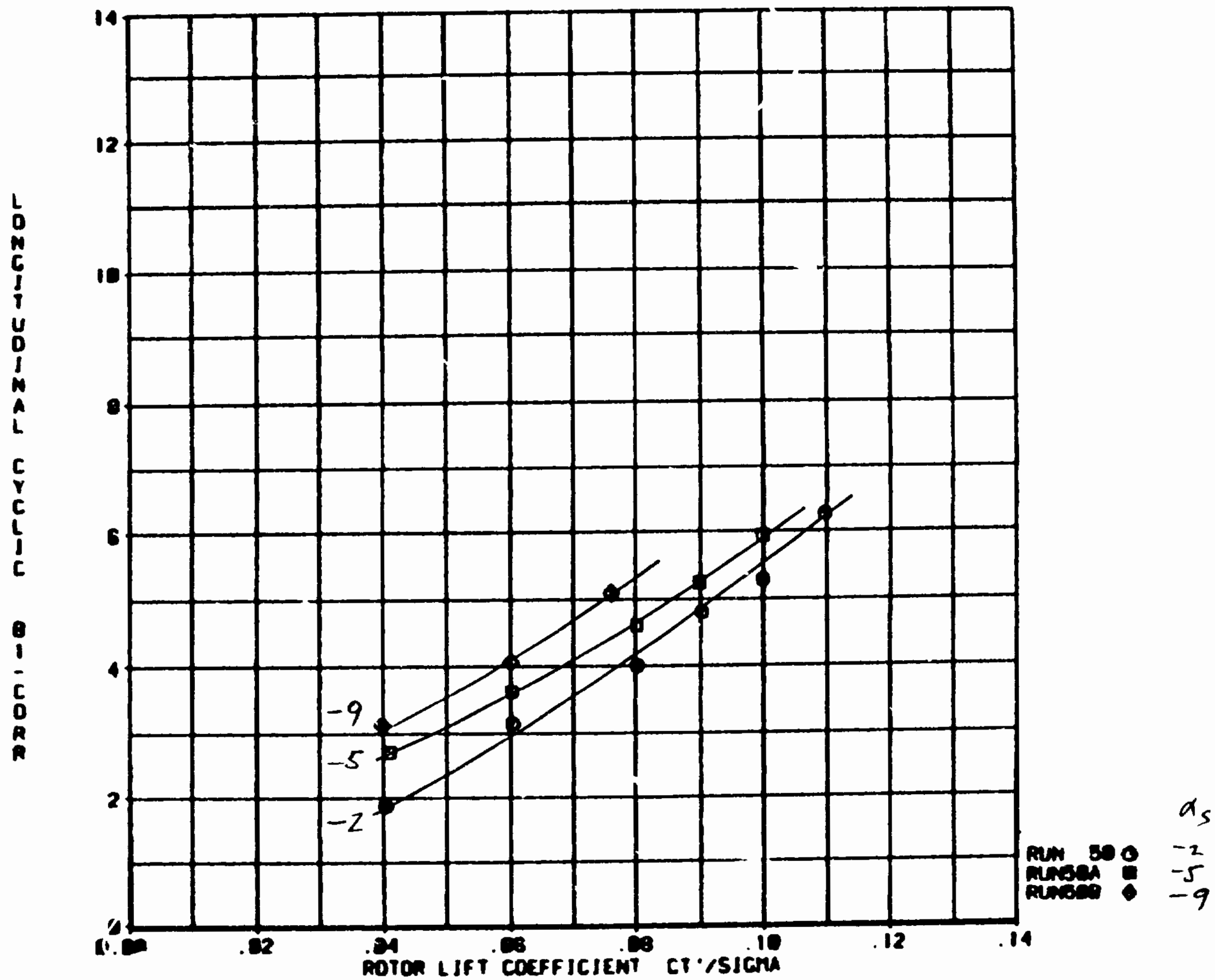


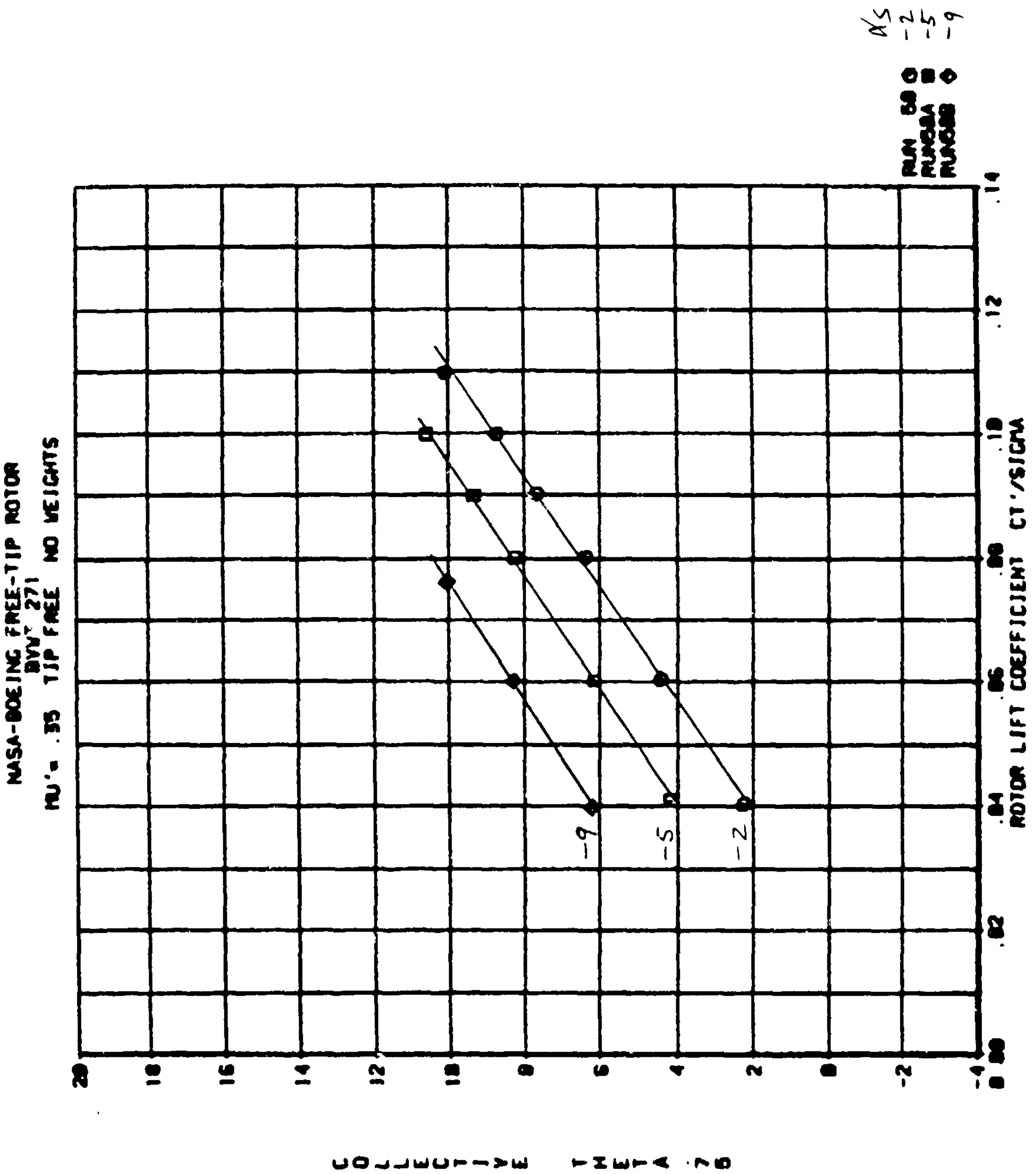

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FREE NO WEIGHTS
ROTOR LIFT COEFFICIENT CT'/SIGMA
DRAG RATIO
RUN 58 O
δs
-2
-5
-9


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .35 TIP FREE NO WEIGHTS
ROTOR LIFT COEFFICIENT CT'/SIGMA
-9
-5
-2


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .38 TIP FREE NO WEIGHTS
LATERAL CYCLIC A1-CORR
ROTOR LIFT COEFFICIENT CT'/SIGMA
8
6
4
2
0
-2
-4
-6
-8
0.00
.02
.04
.06
.08
.10
.12
.14
-2
-5
-9
α_s
RUN 58 -2
RUN58A -5
RUN58B -9

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FREE NO WEIGHTS




NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .35 TIP FREE NO WEIGHTS
ROTOR LIFT COEFFICIENT CT'/SIGMA
RUN 58
-2
-5
-9

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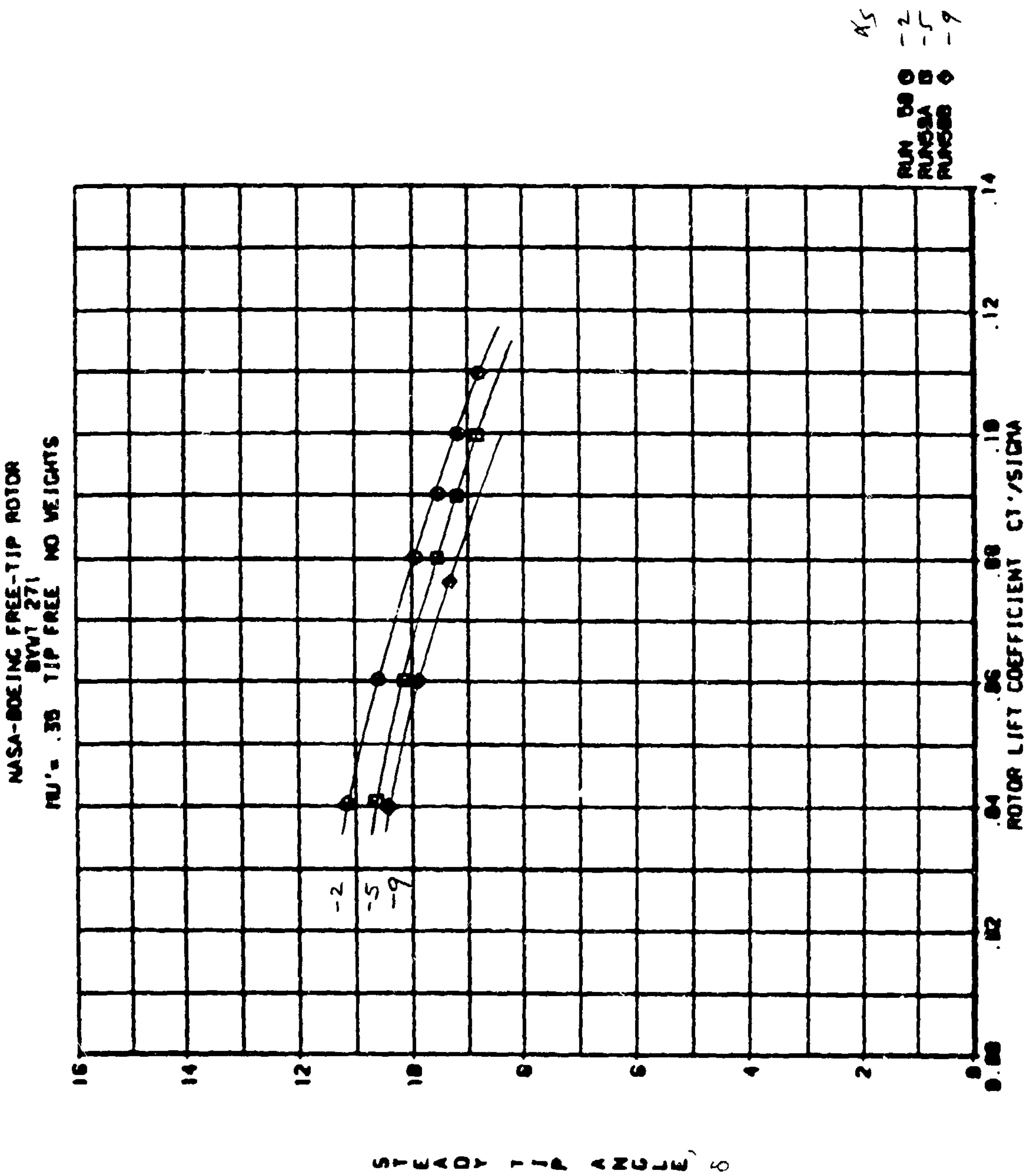

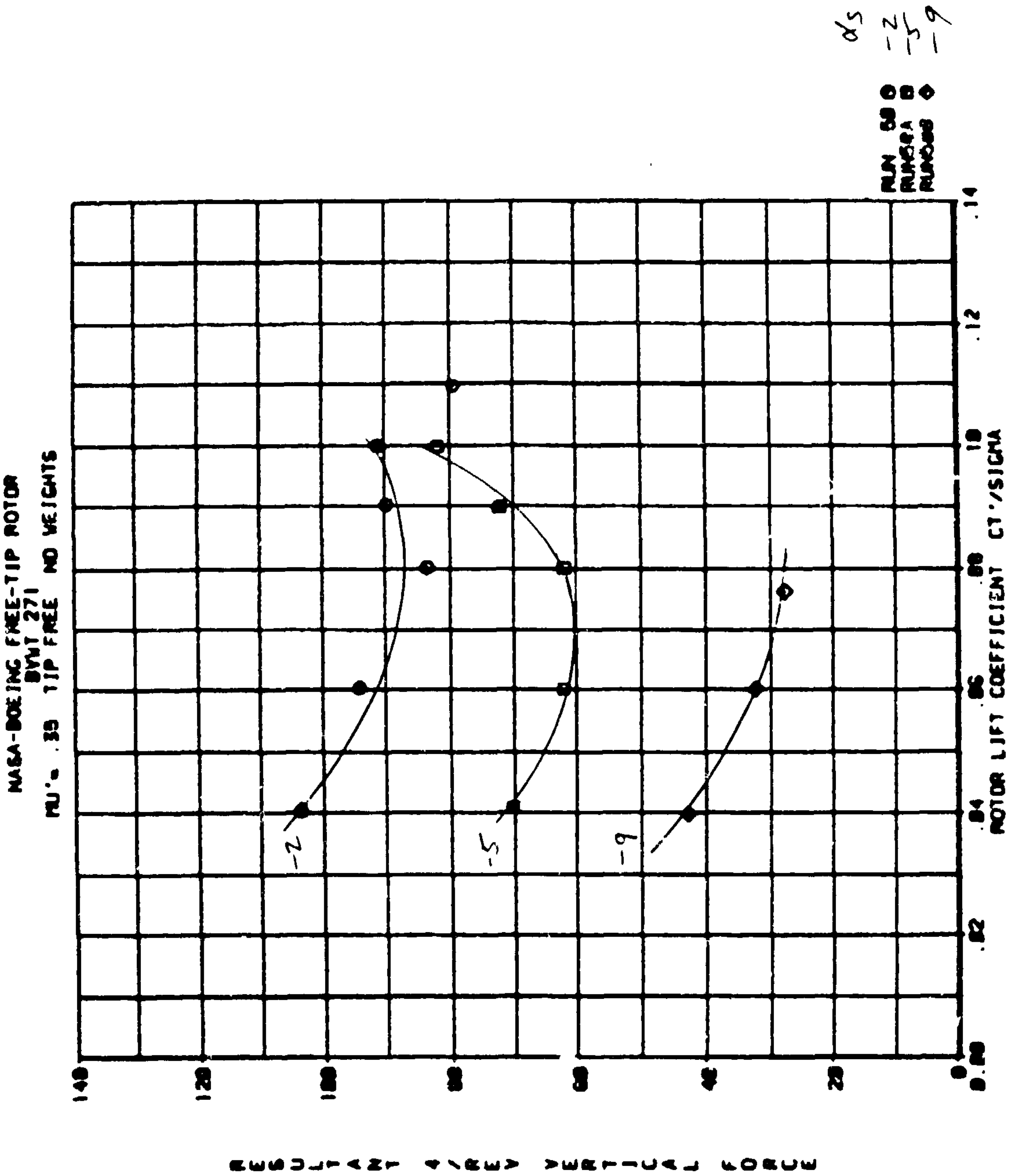
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .35 TIP FREE NO WEIGHTS
RUN 58
RUN58A
RUN58B
αs
-2
-5
-9
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
20
40
60
80
100
120
140

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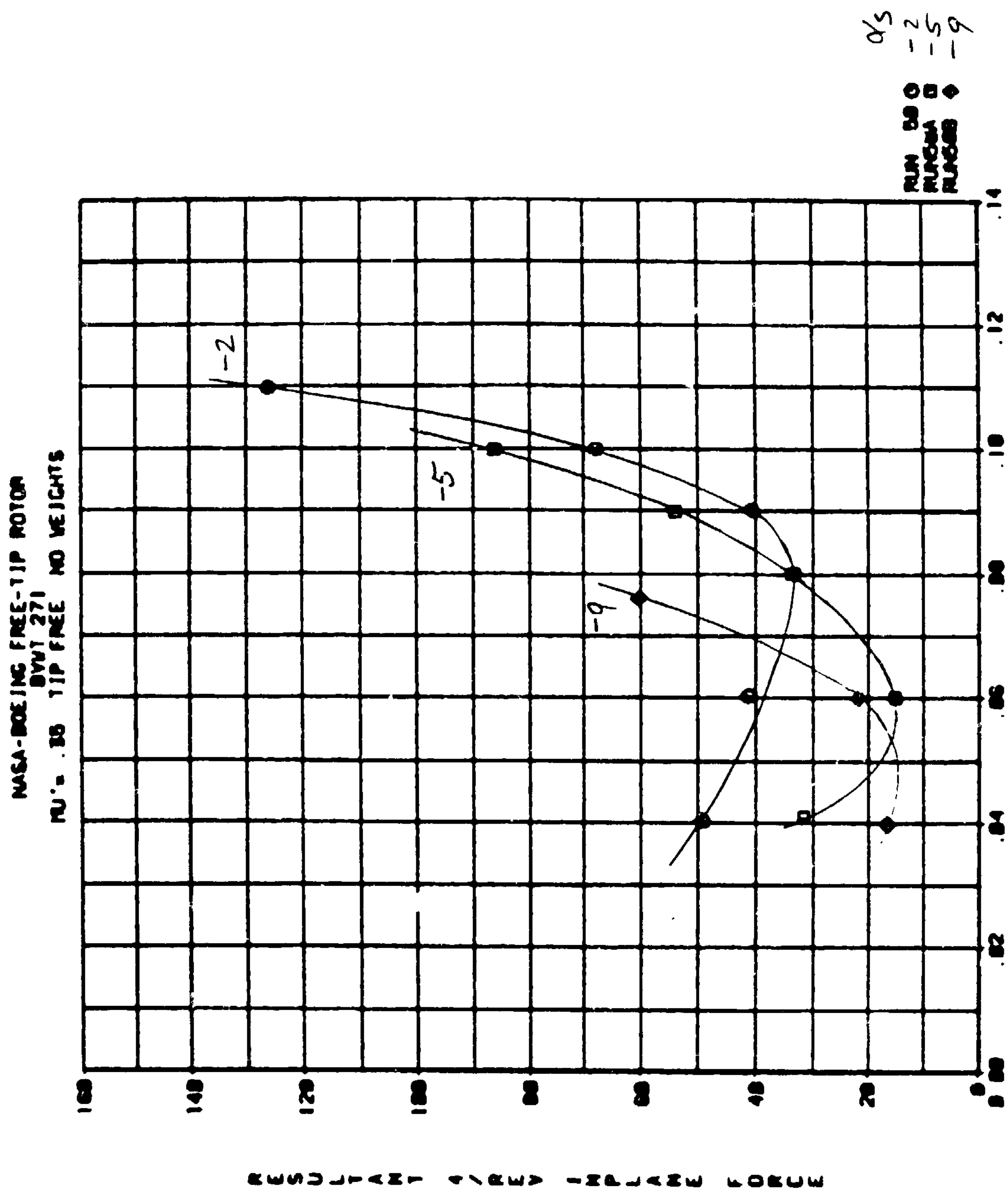

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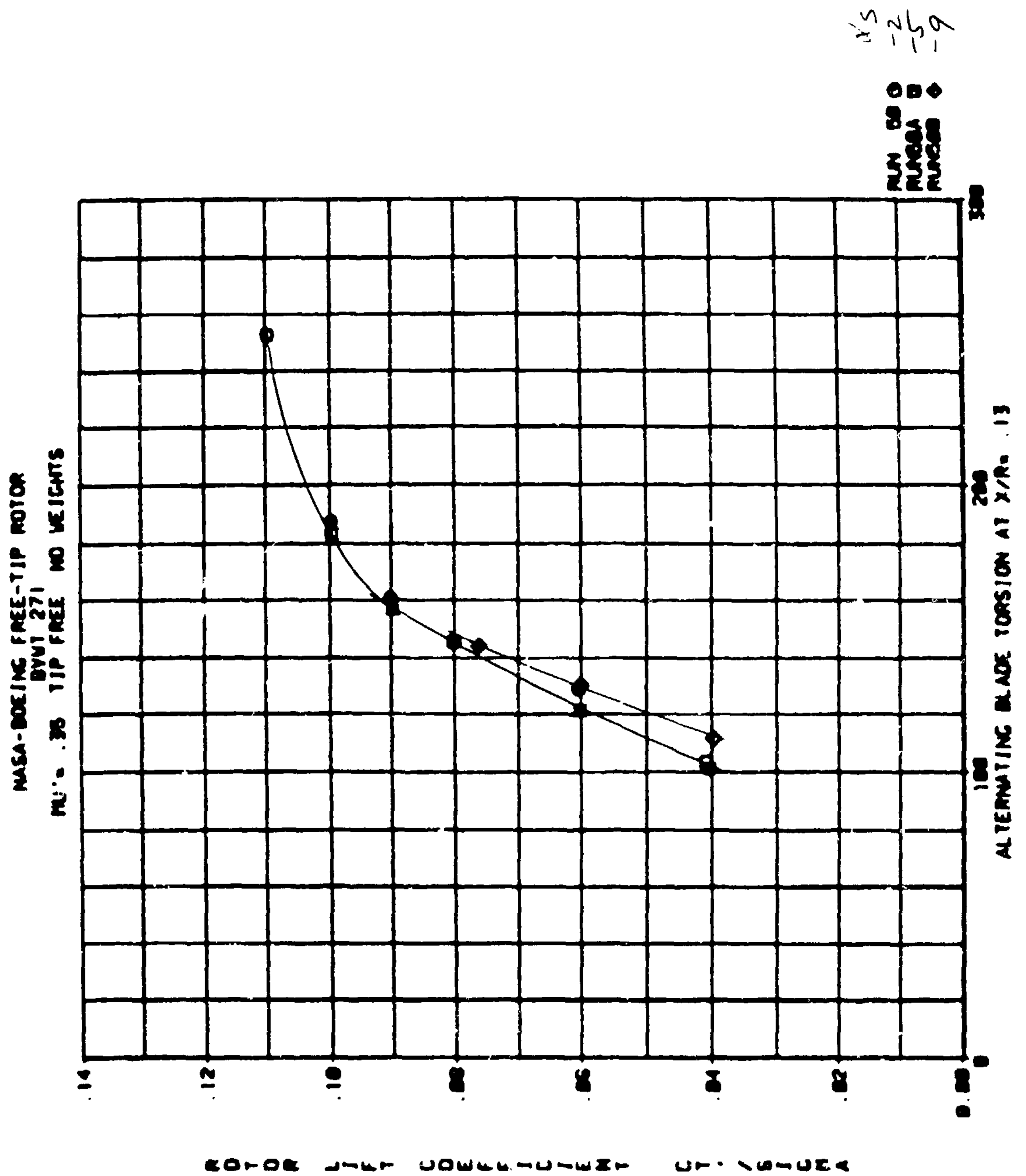
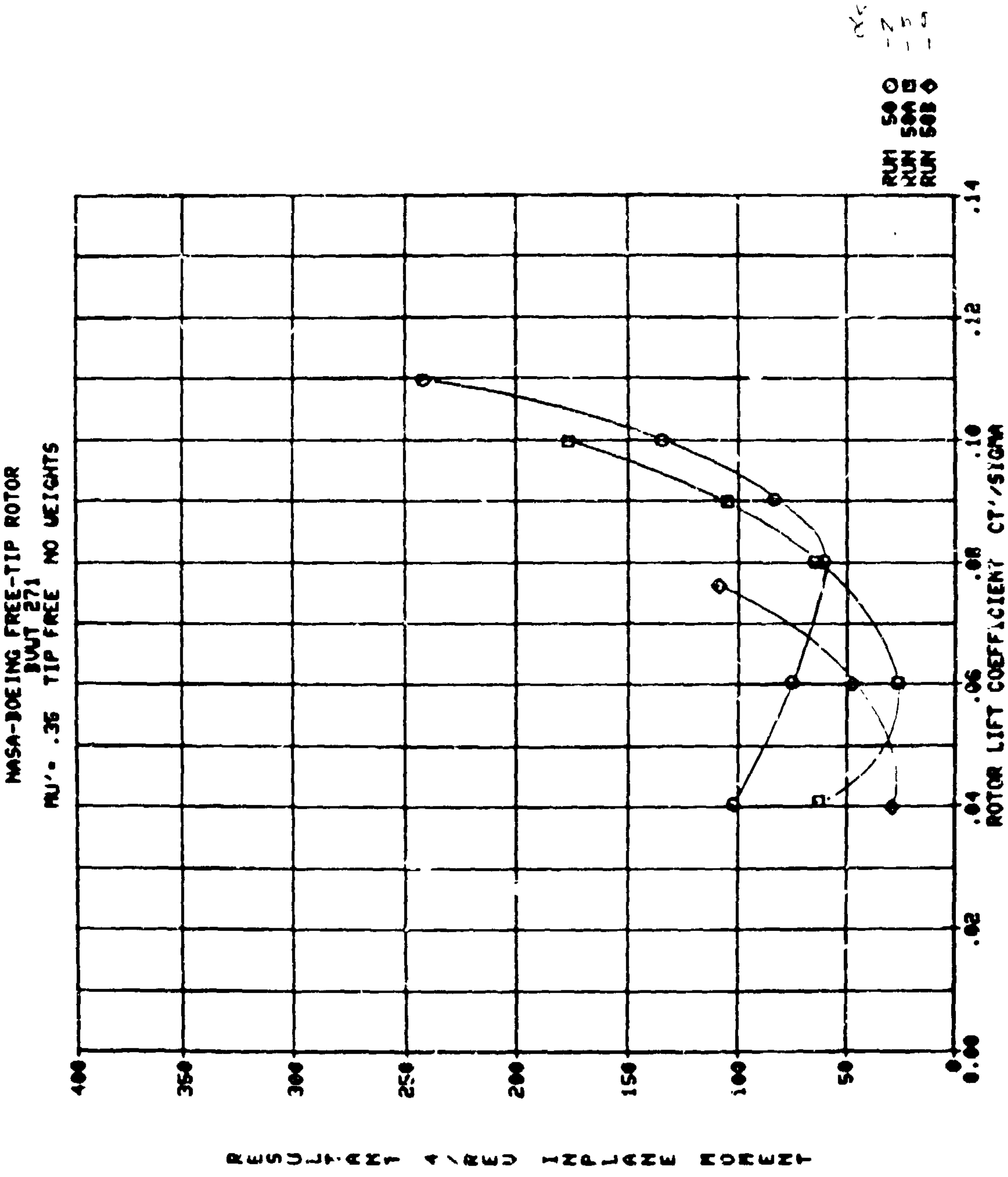
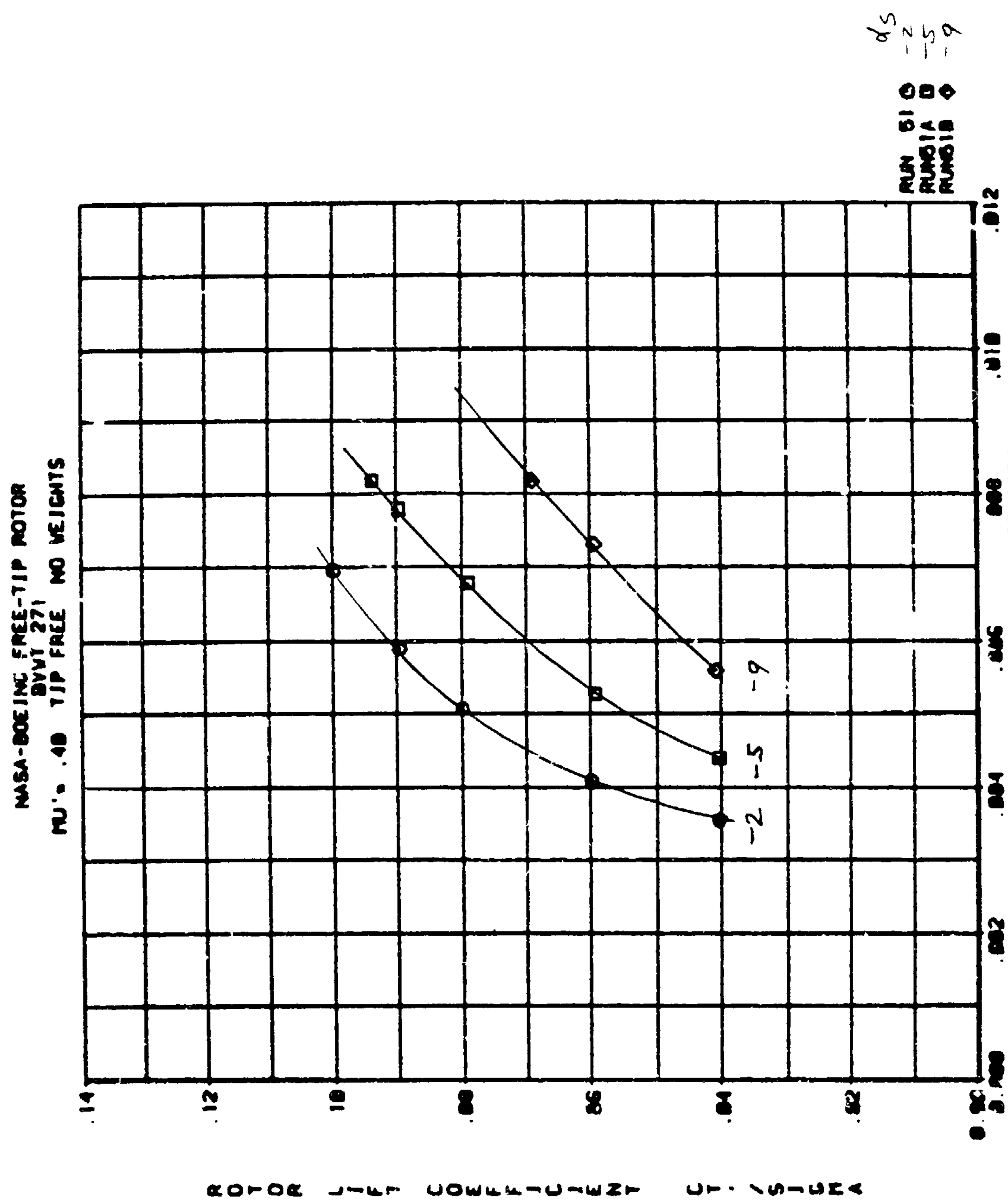



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .36 TIP FREE NO WEIGHTS
RUN 50 O
RUN 50A □
RUN 50B ◇
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
50
100
150
200
250
300
350
400

OF POOR QUALITY



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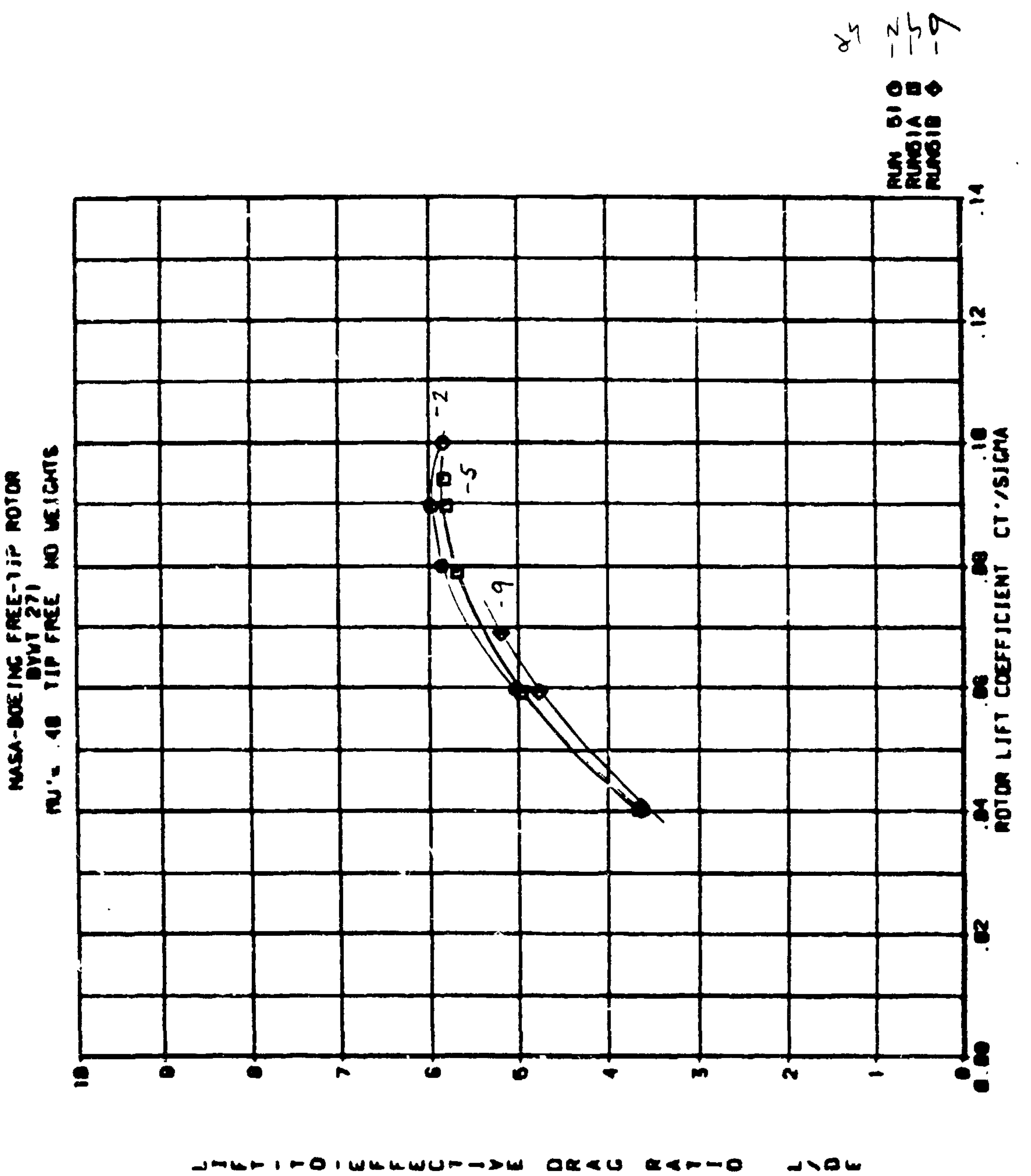
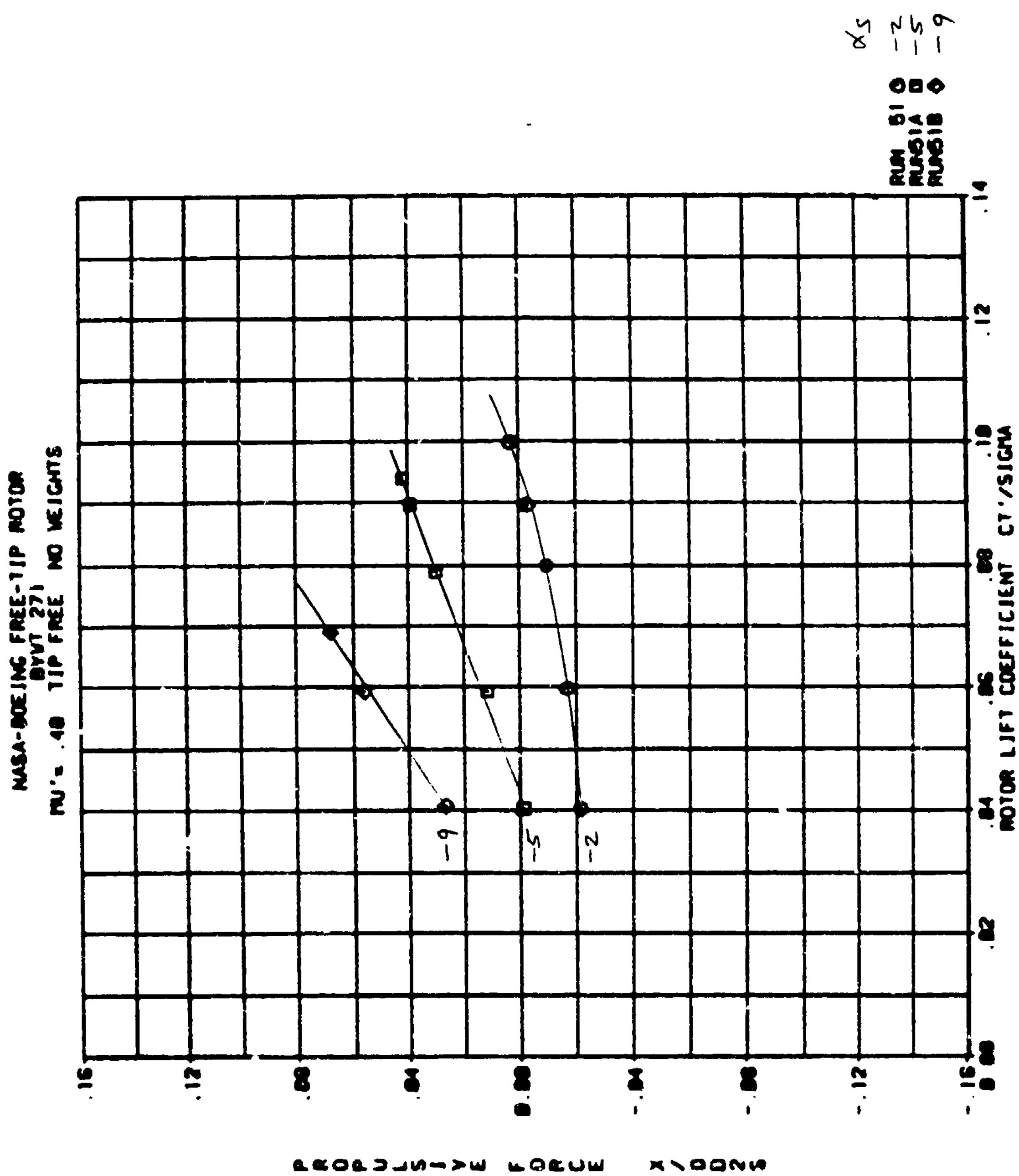
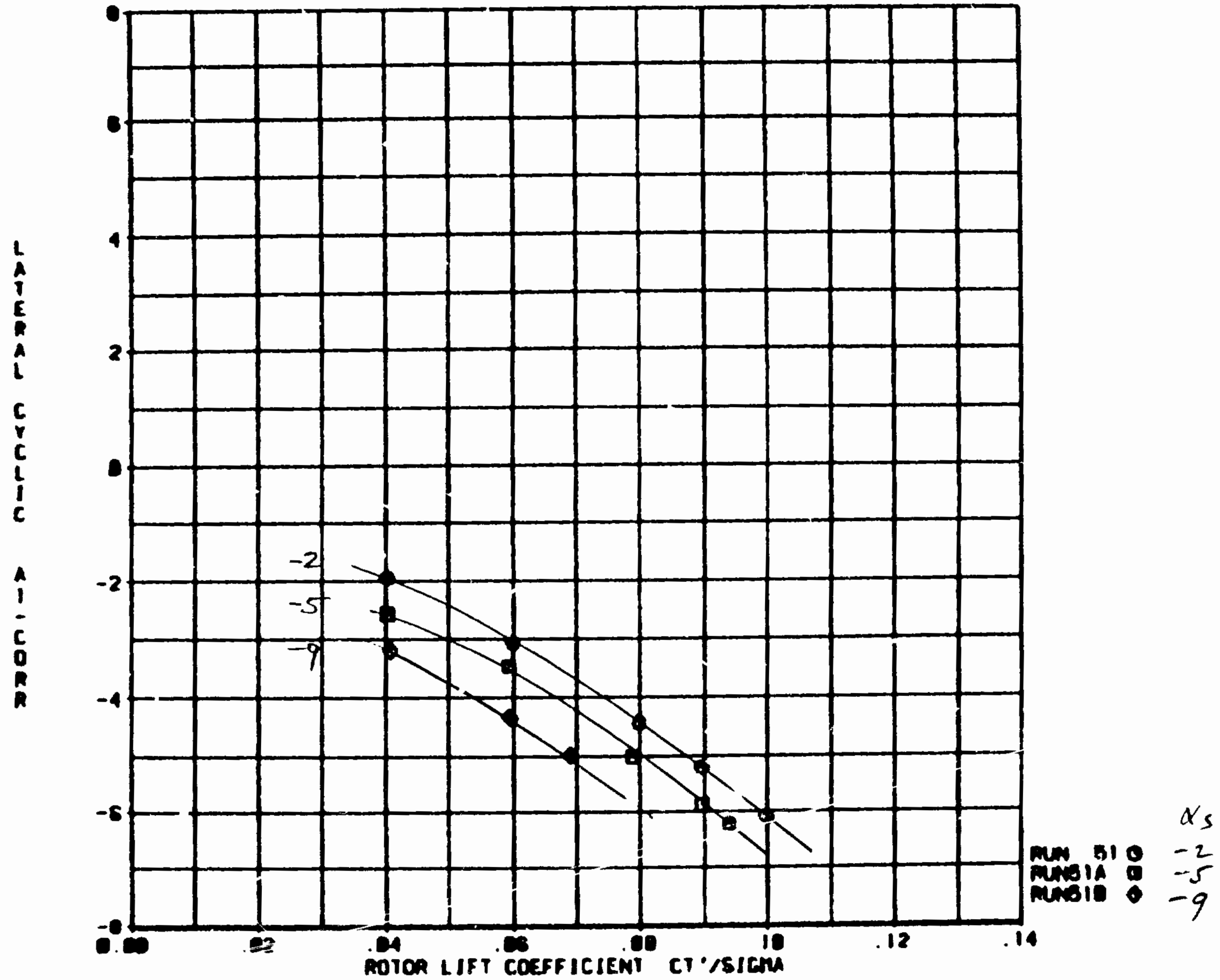
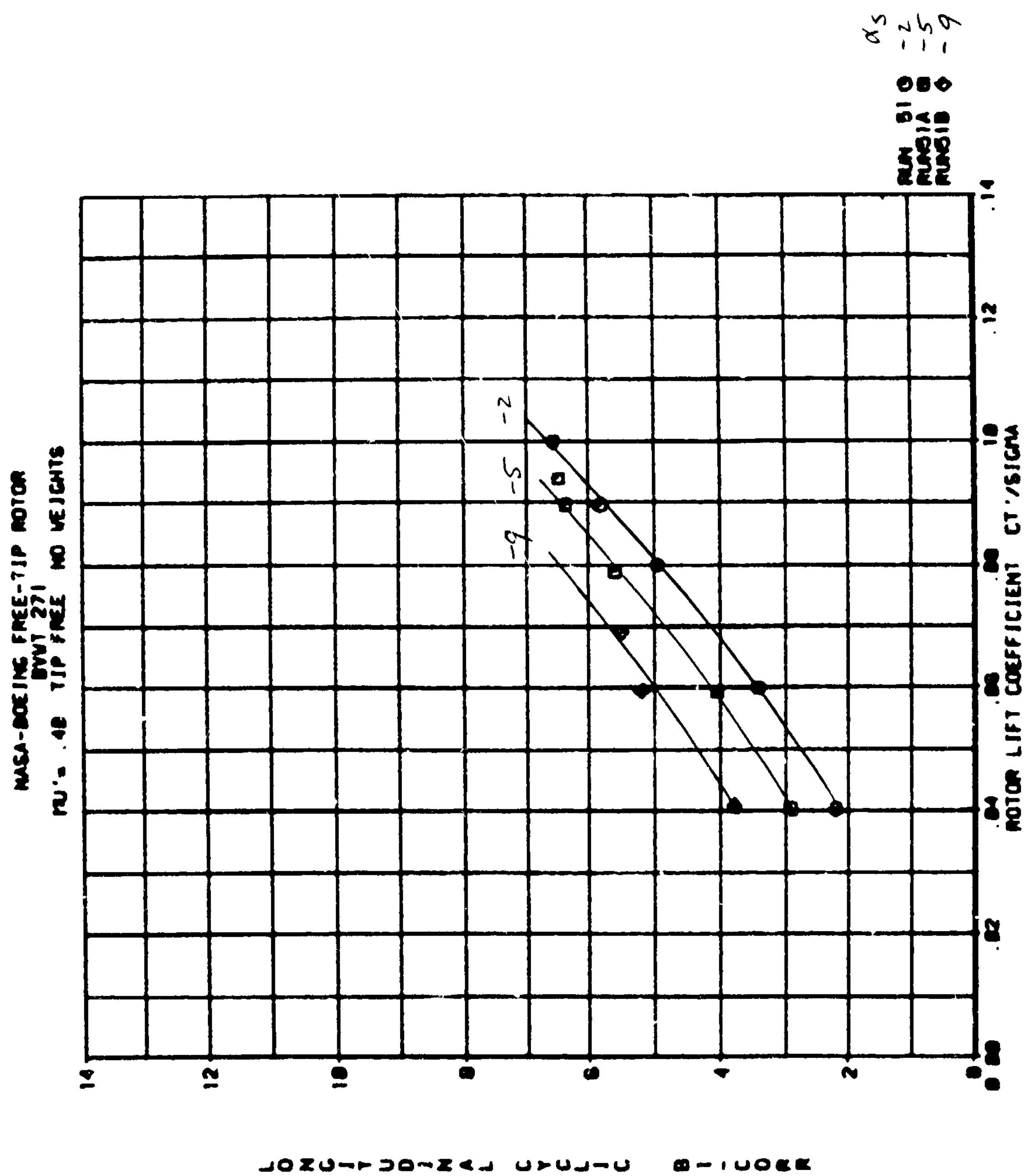
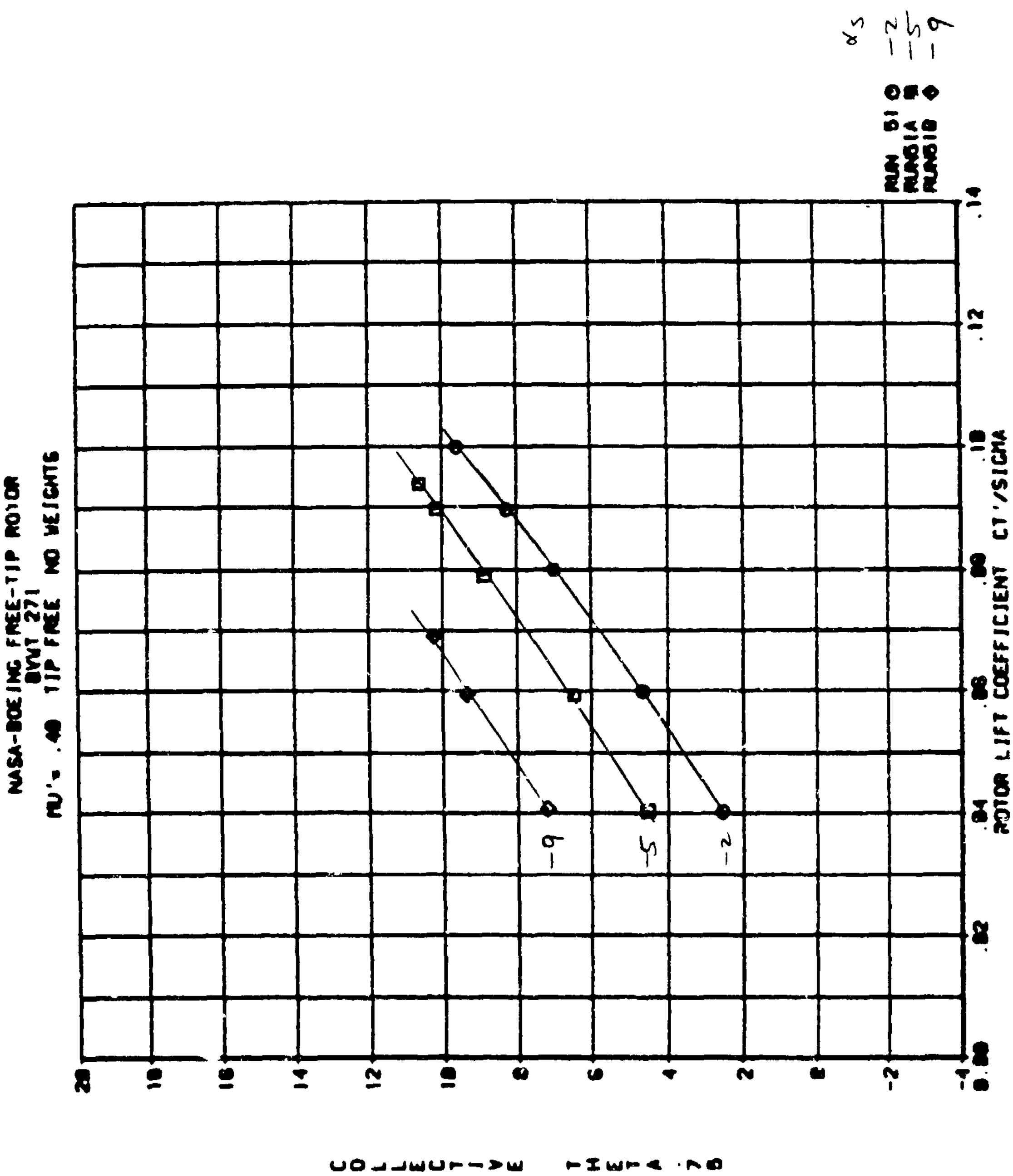



NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .40 TIP FREE NO WEIGHTS
RUN 51
RUN51A
RUN51B
δs
-2
-5
-9
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
.16
.12
.08
.04
0.00
-.04
-.08
-.12
-.16

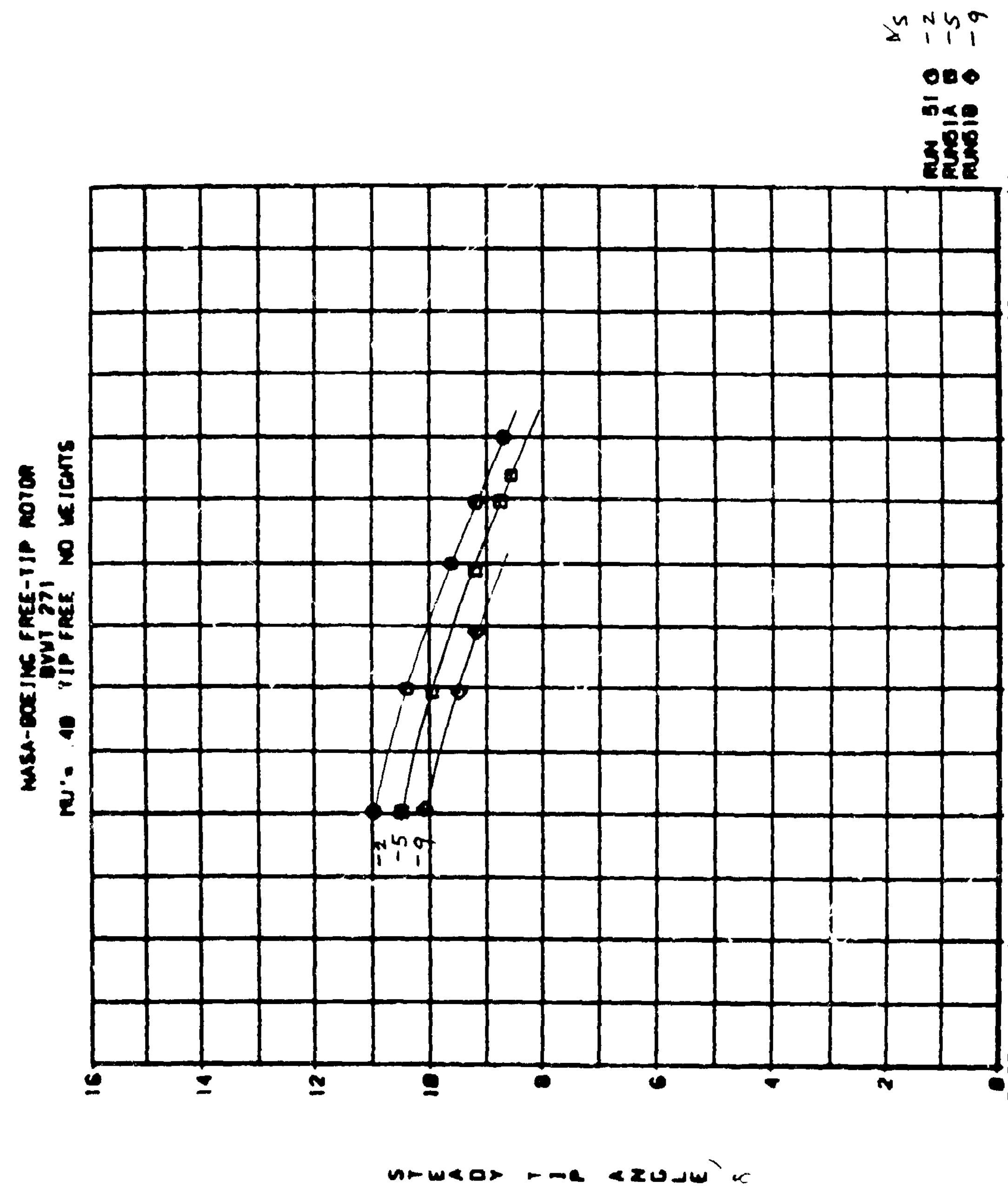
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .40 TIP FREE NO WEIGHTS



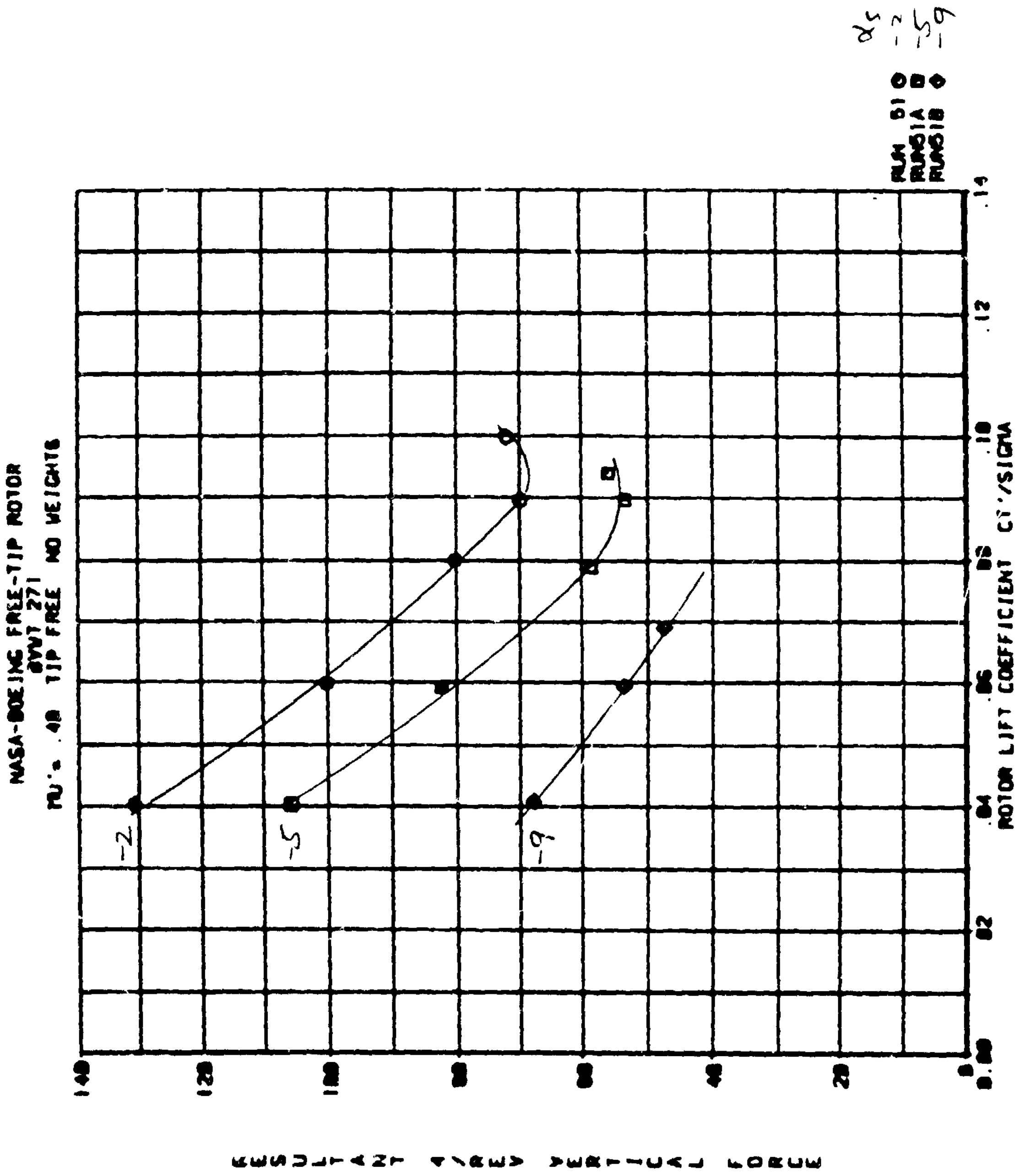

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .48 TIP FREE NO WEIGHTS
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00 .02 .04 .06 .08 .10 .12 .14
0 2 4 6 8 10 12 14
RUN 51 ○
RUN51A □
RUN51B ◇
αs -2 -5 -9
-2
-5
-9

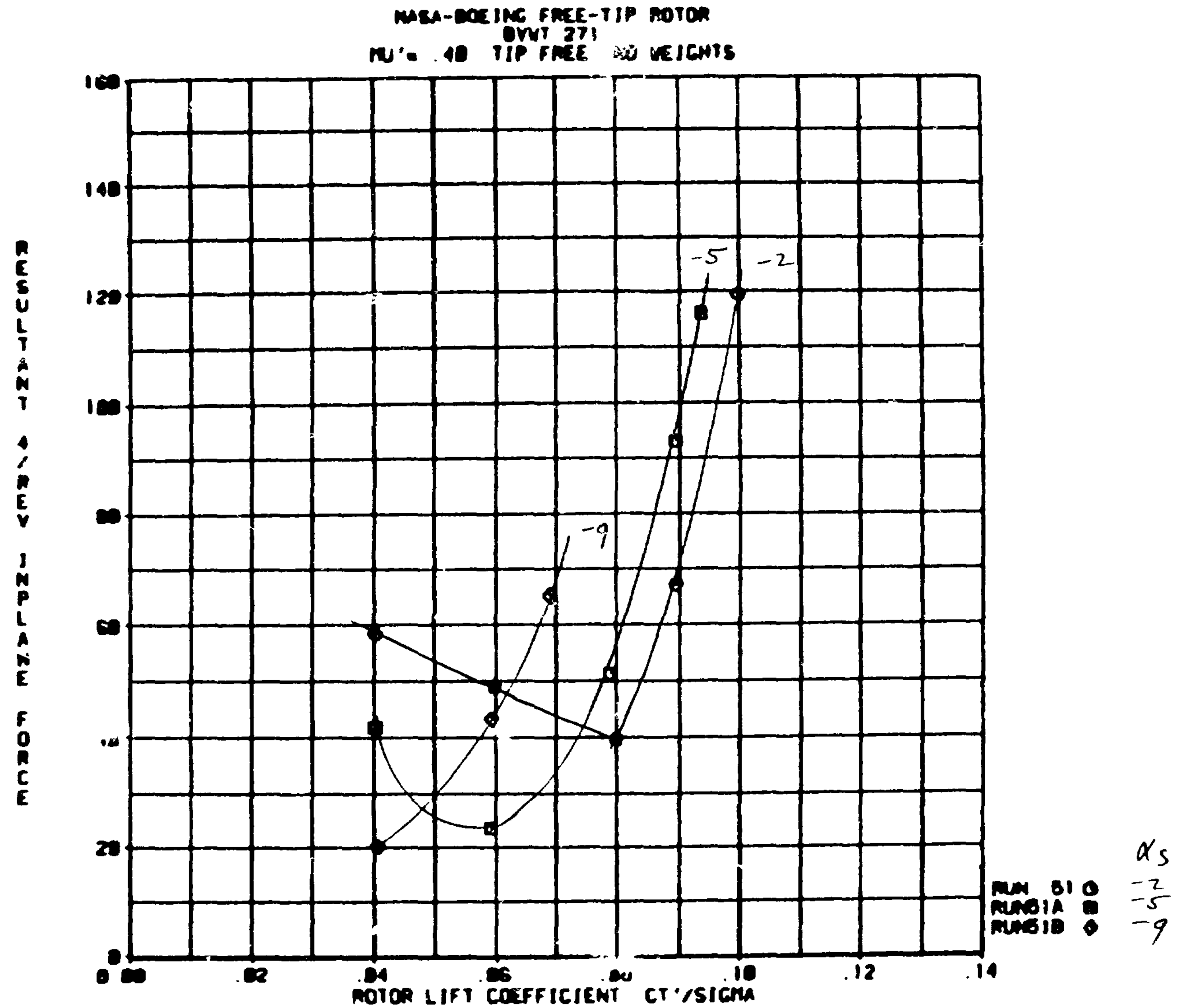


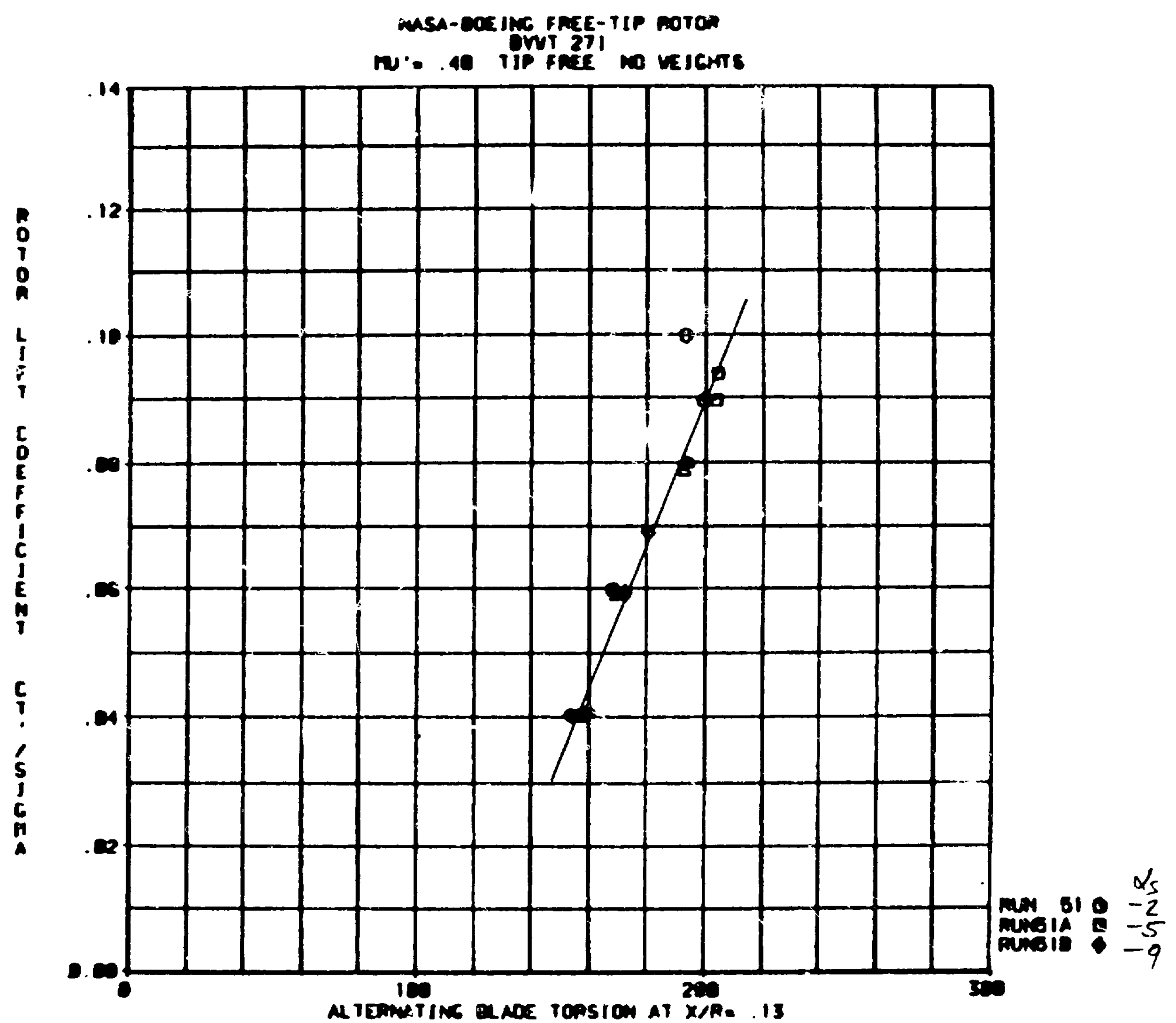
NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .40 TIP FREE NO WEIGHTS
ROTOR LIFT COEFFICIENT CT'/SIGMA
RUN 51
RUN51A
RUN51B
αs
-2
-5
-9

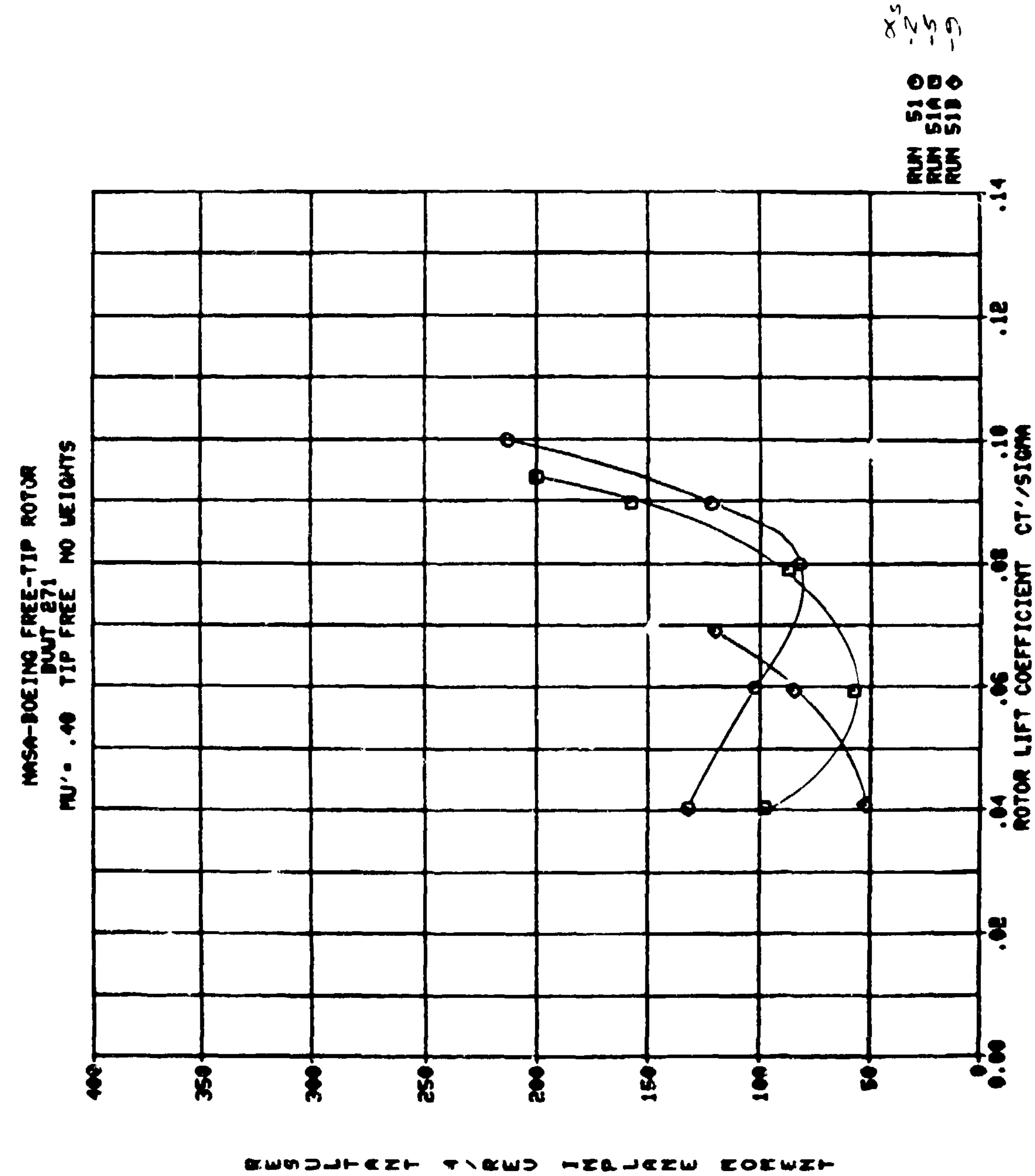

NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .40 TIP FREE NO WEIGHTS
RUN 51
RUN51A
RUN51B
-2
-5
-9
ROTOR LIFT COEFFICIENT CT'/SIGMA
0.00
.02
.04
.06
.08
.10
.12
.14
0
2
4
6
8
10
12
14
16
STEADY TIP ANGLE

OR
OF


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .40 TIP FREE NO WEIGHTS
ROTOR LIFT COEFFICIENT CT'/SIGMA
RUN 51
RUN51A
RUN51B
αs -2 -5 -9
-2
-5
-9
0.00
.02
.04
.06
.08
.10
.12
.14
0
20
40
60
80
100
120
140


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .40 TIP FREE NO WEIGHTS
RESULTANT 4/REV INPLANE FORCE
ROTOR LIFT COEFFICIENT CT'/SIGMA
0
20
40
60
80
100
120
140
160
0.00
.02
.04
.06
.08
.10
.12
.14
RUN 51
RUN61A
RUN61B
α_s
-2
-5
-9


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU's .40 TIP FREE NO WEIGHTS
ROTOR LIFT COEFFICIENT CT'/SIGMA
.14
.12
.10
.08
.06
.04
.02
0.00
0
100
200
300
ALTERNATING BLADE TORSION AT X/R= .13
RUN 51 -2
RUN51A -5
RUN51B -9
α_s


NASA-BOEING FREE-TIP ROTOR
BVWT 271
MU'= .40 TIP FREE NO WEIGHTS
RUN 51
RUN 51A
RUN 51B
ROTOR LIFT COEFFICIENT CT'/SIGMA
RESULTANT 4/REV INPLANE MOMENT
0.00
.02
.04
.06
.08
.10
.12
.14
0
50
100
150
200
250
300
350
400

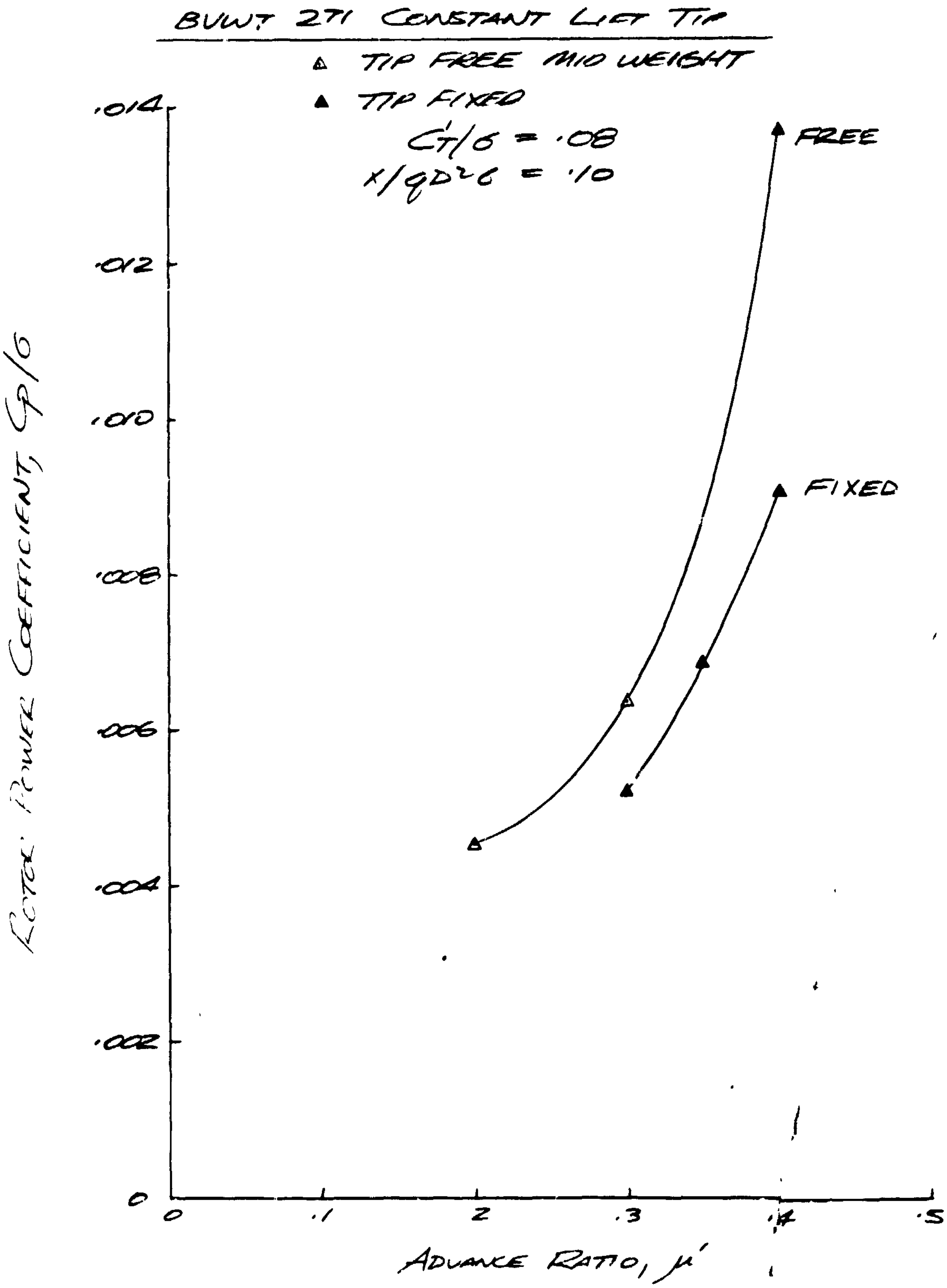
APPENDIX B. DATA CROSS PLOTS

Using the basic test data presented in Appendix A, extensive cross plots against advance ratio were made for the mid weight condition with the tip fixed and with it free. This data is presented for the following range of C'_T/σ and $\bar{X}$.

At each $\bar{X}$ and C'_T the order of the plots is

C_P/σ vs. μ'
L/D_E vs. μ'
α_S vs. μ'
$\theta_{.75}$ vs. μ'
A_1 vs. μ'
B_1 vs. μ'
δ vs. μ'

4/rev resultant vertical force vs. μ'
4/rev resultant inplane force vs. μ'


BUWT 271 CONSTANT LIFT TIP
△ TIP FREE MID WEIGHT
▲ TIP FIXED
$C_T'/\sigma = .08$
$X/qD^2\sigma = .10$
FREE
FIXED
ROTOR POWER COEFFICIENT, C_P/σ
.014
.012
.010
.008
.006
.004
.002
0
0
.1
.2
.3
.4
.5
ADVANCE RATIO, μ'

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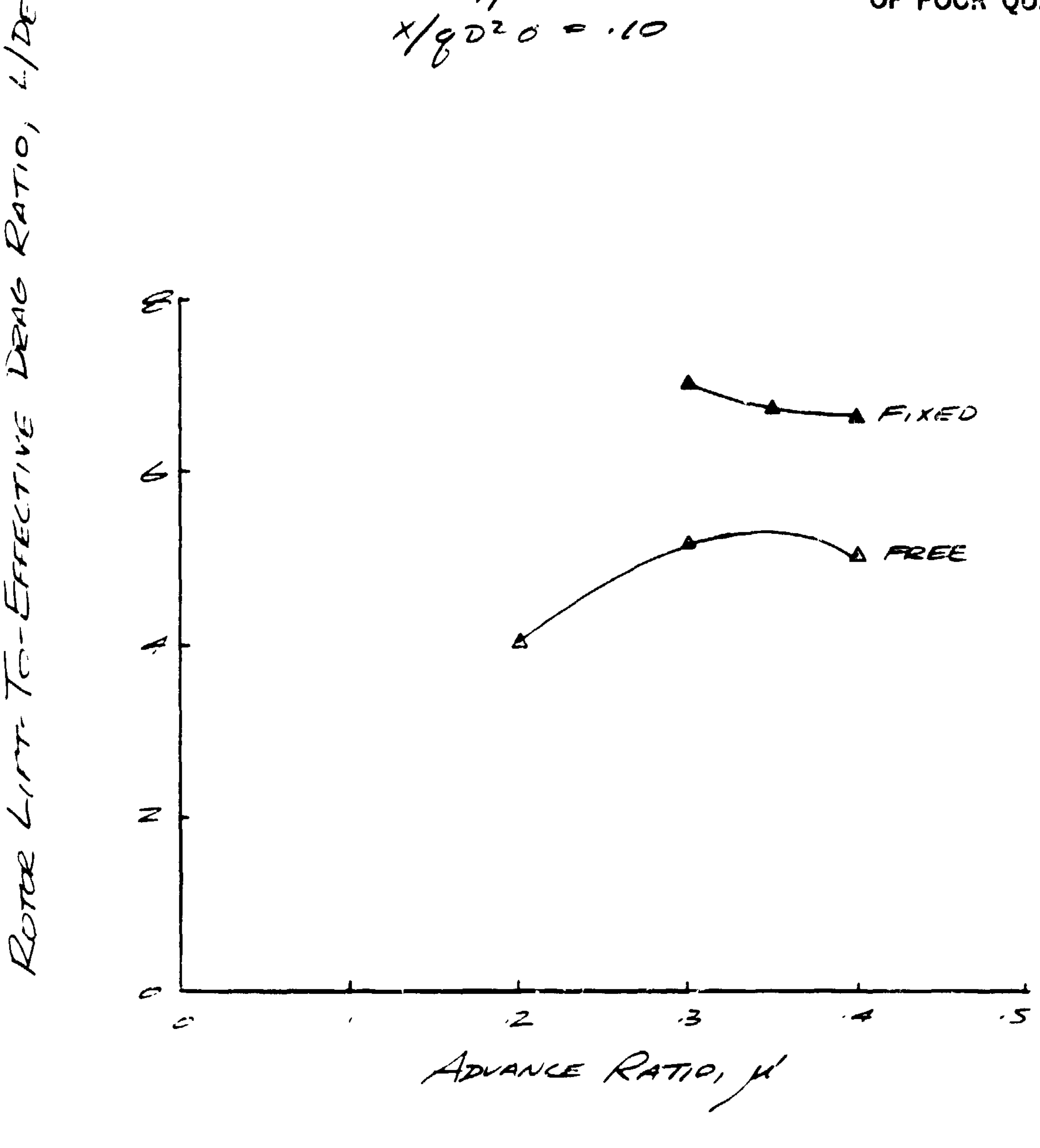
BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT

▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = .10$



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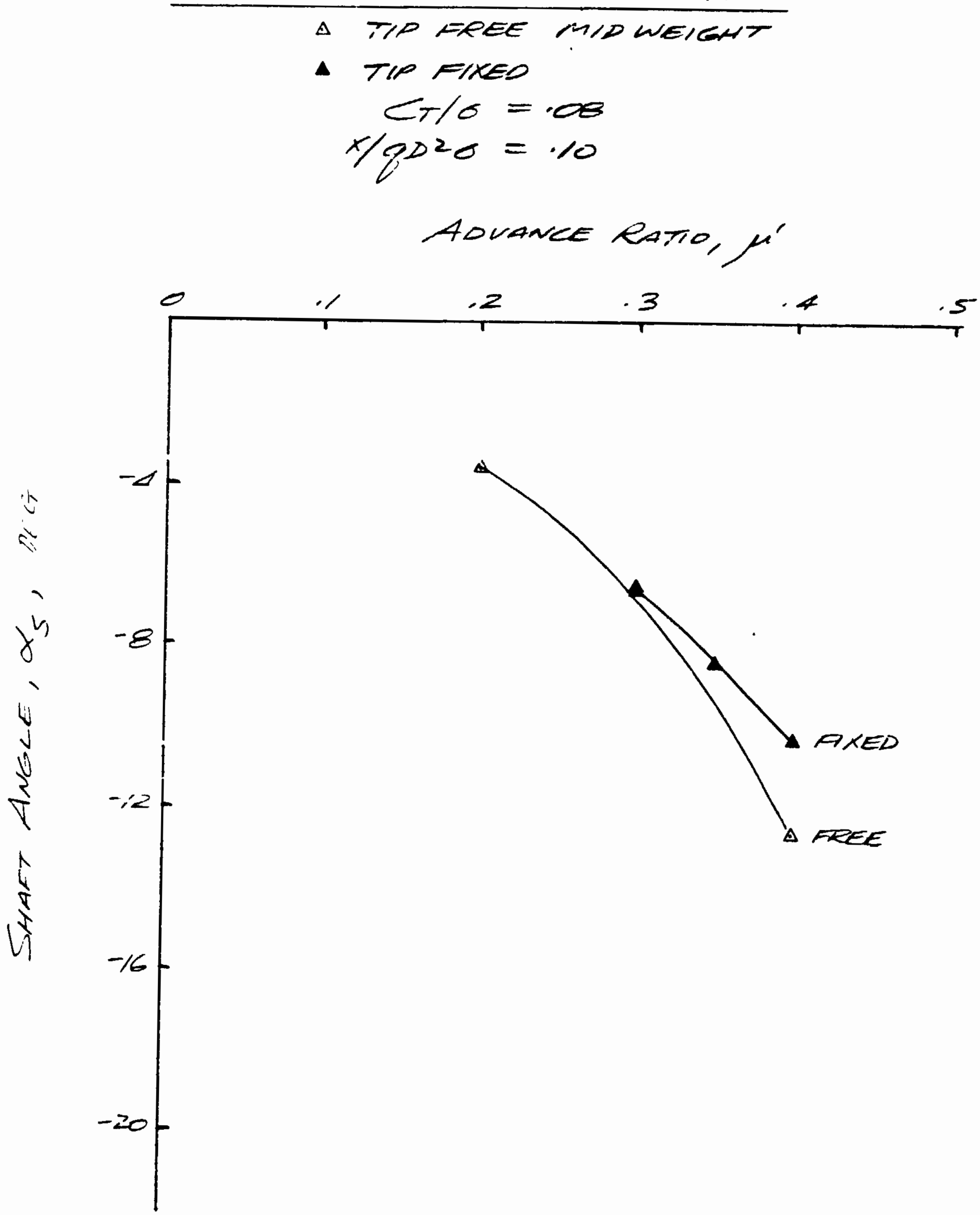
EVWT 271 CONSTANT LIFT TIP



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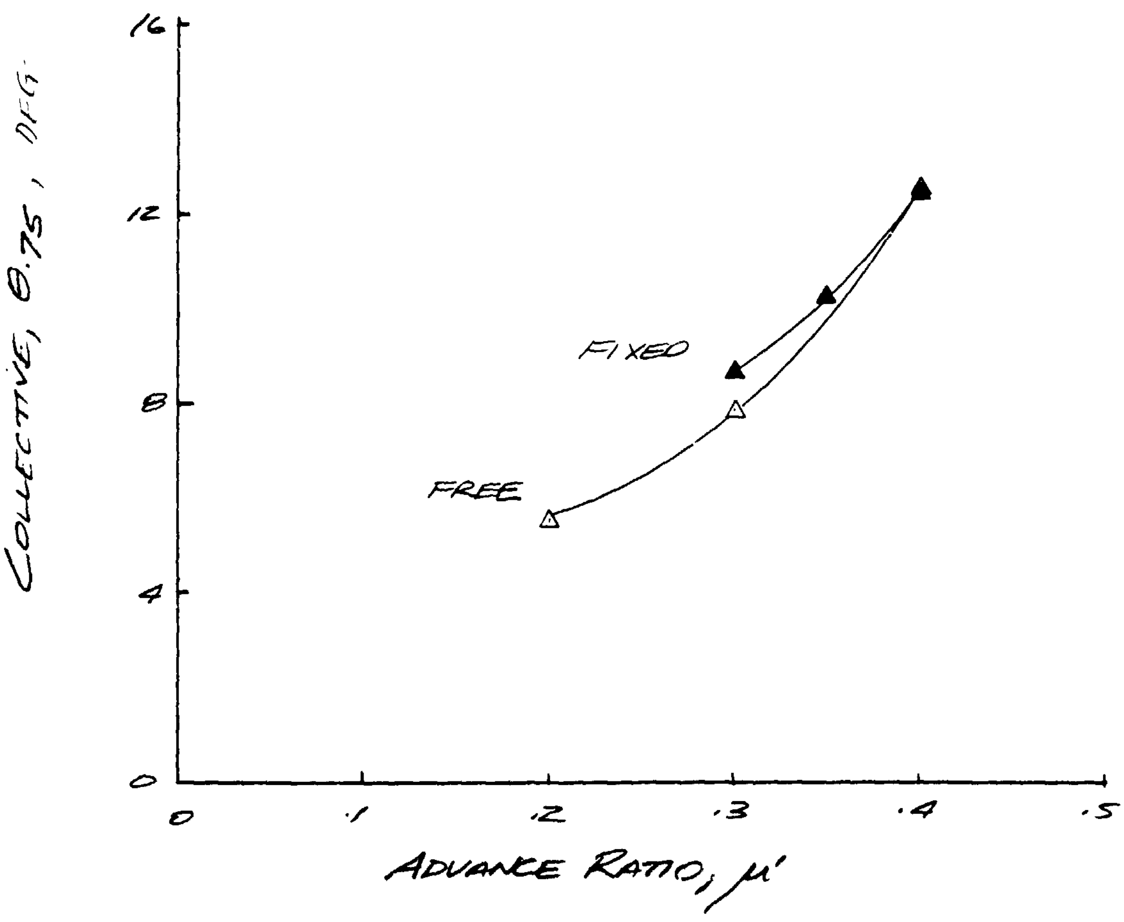
BWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = .10$



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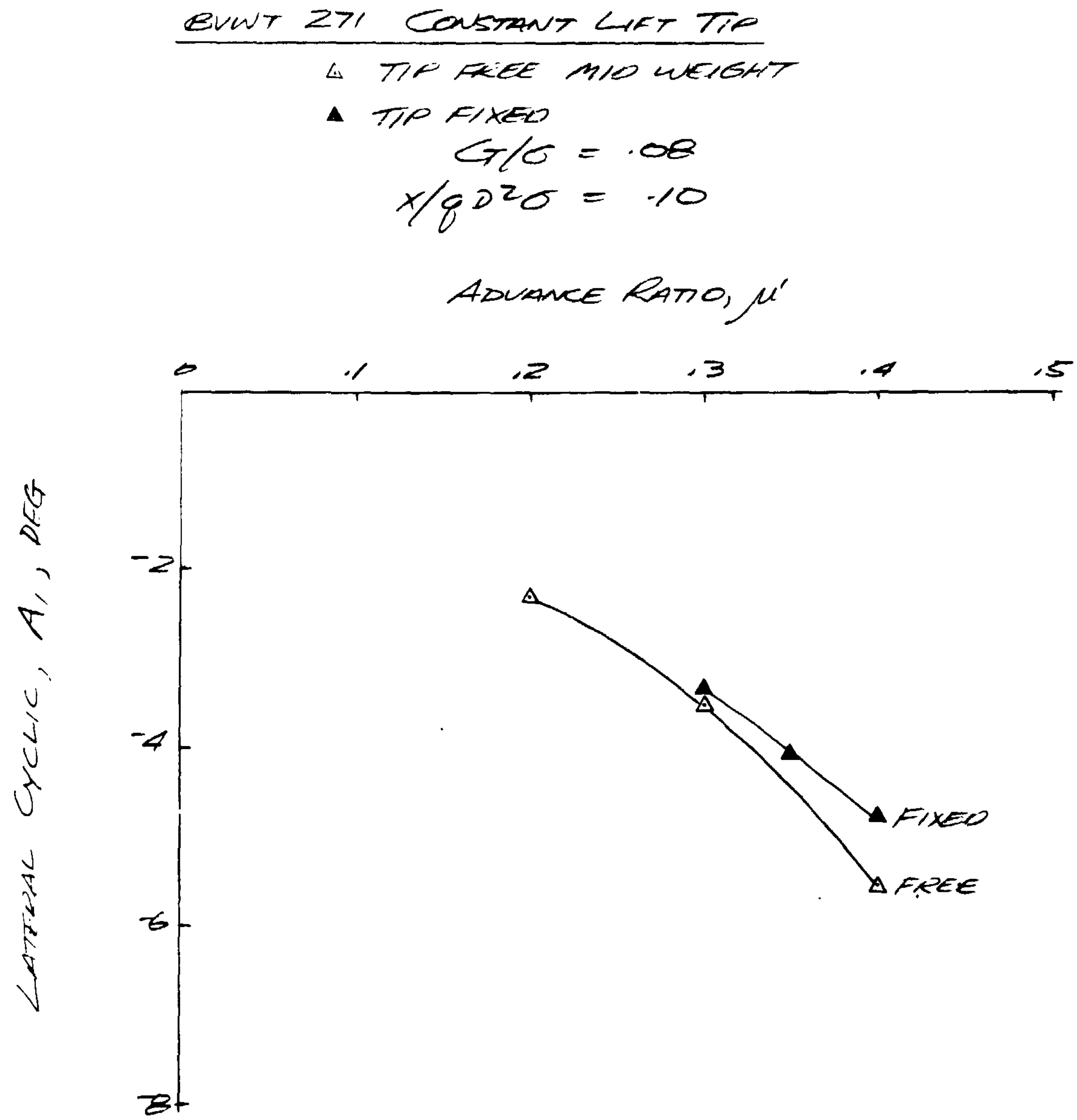
BVWT 271 CONSTANT LIFT TIP
TIP FREE MID WEIGHT
TIP FIXED
G/σ = .08
X/qD²σ = .10
ADVANCE RATIO, μ'
0
.1
.2
.3
.4
.5
LATERAL CYCLIC, A1, DEG
-2
-4
-6
-8
FIXED
FREE

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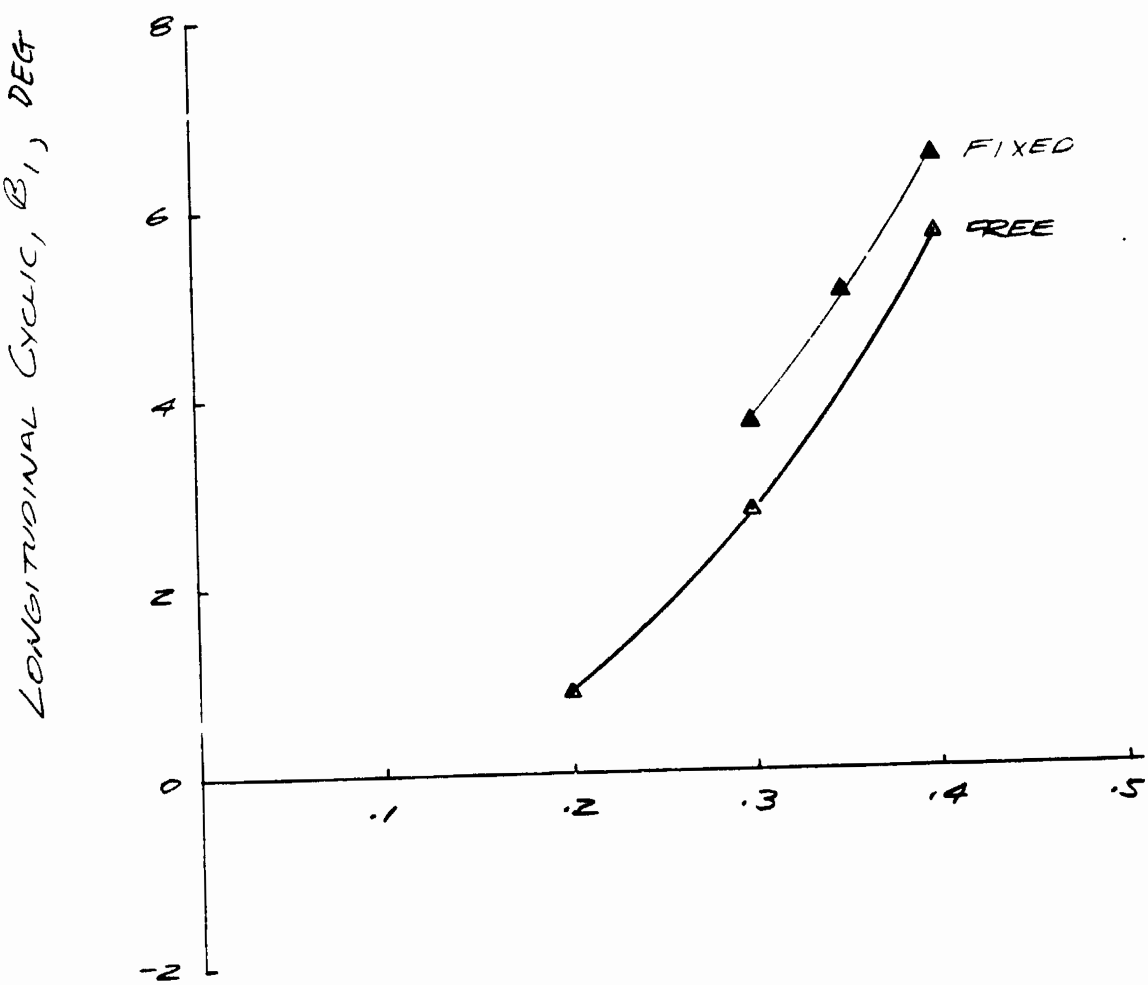
BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = .10$



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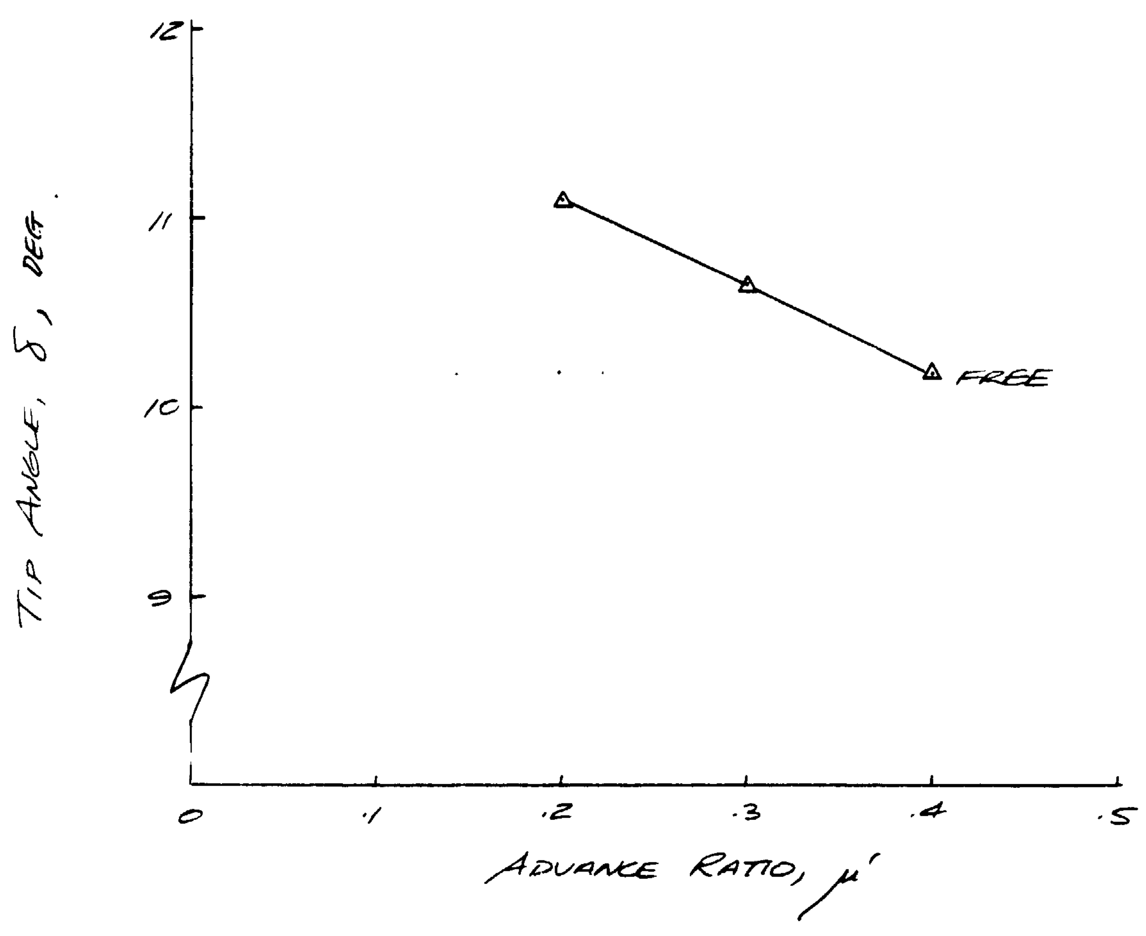
BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
(TIP FIXED $\delta=0$)

$C_T/\sigma = .08$
$X/qD^2\sigma = .10$



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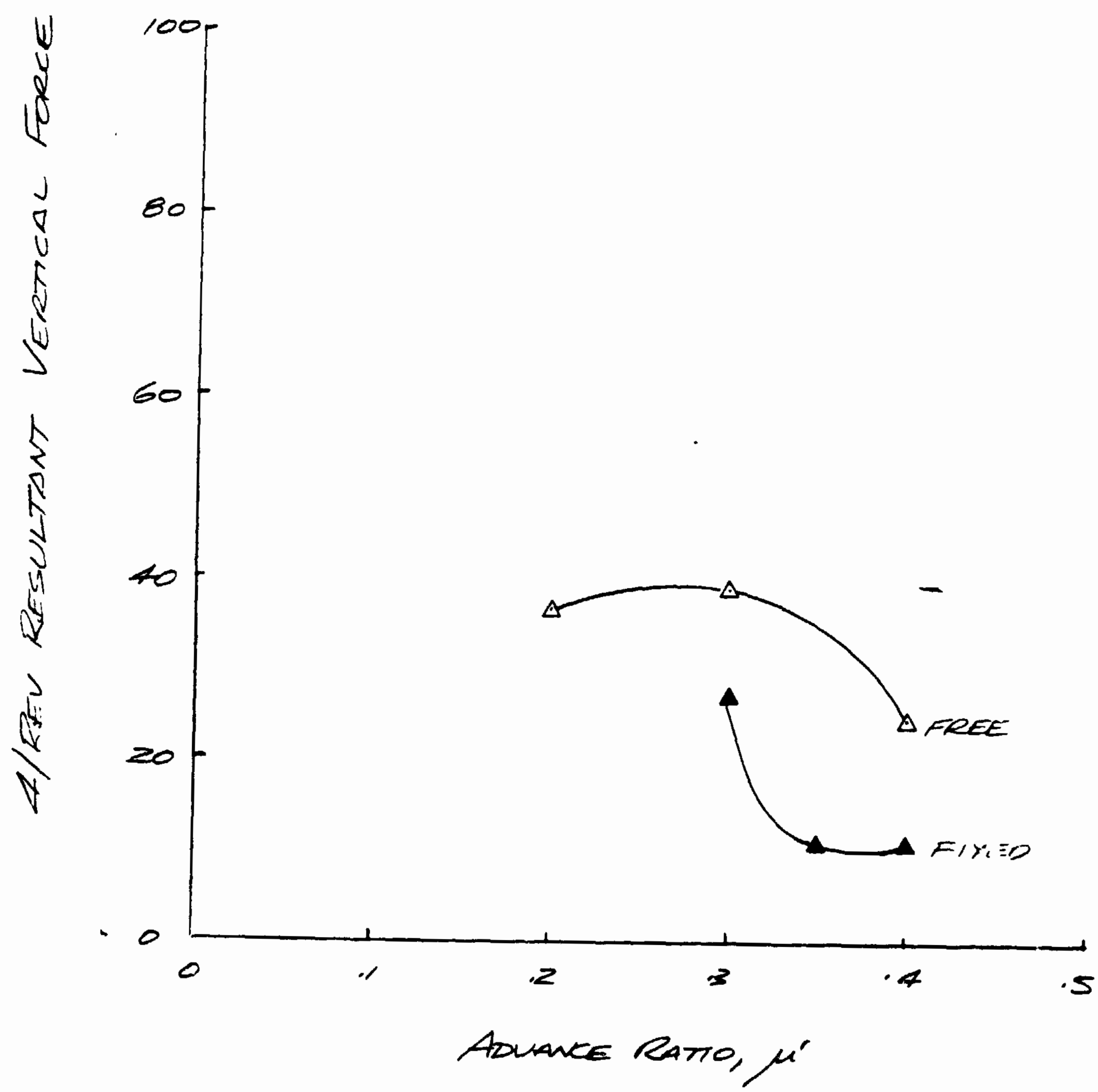
BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = .10$



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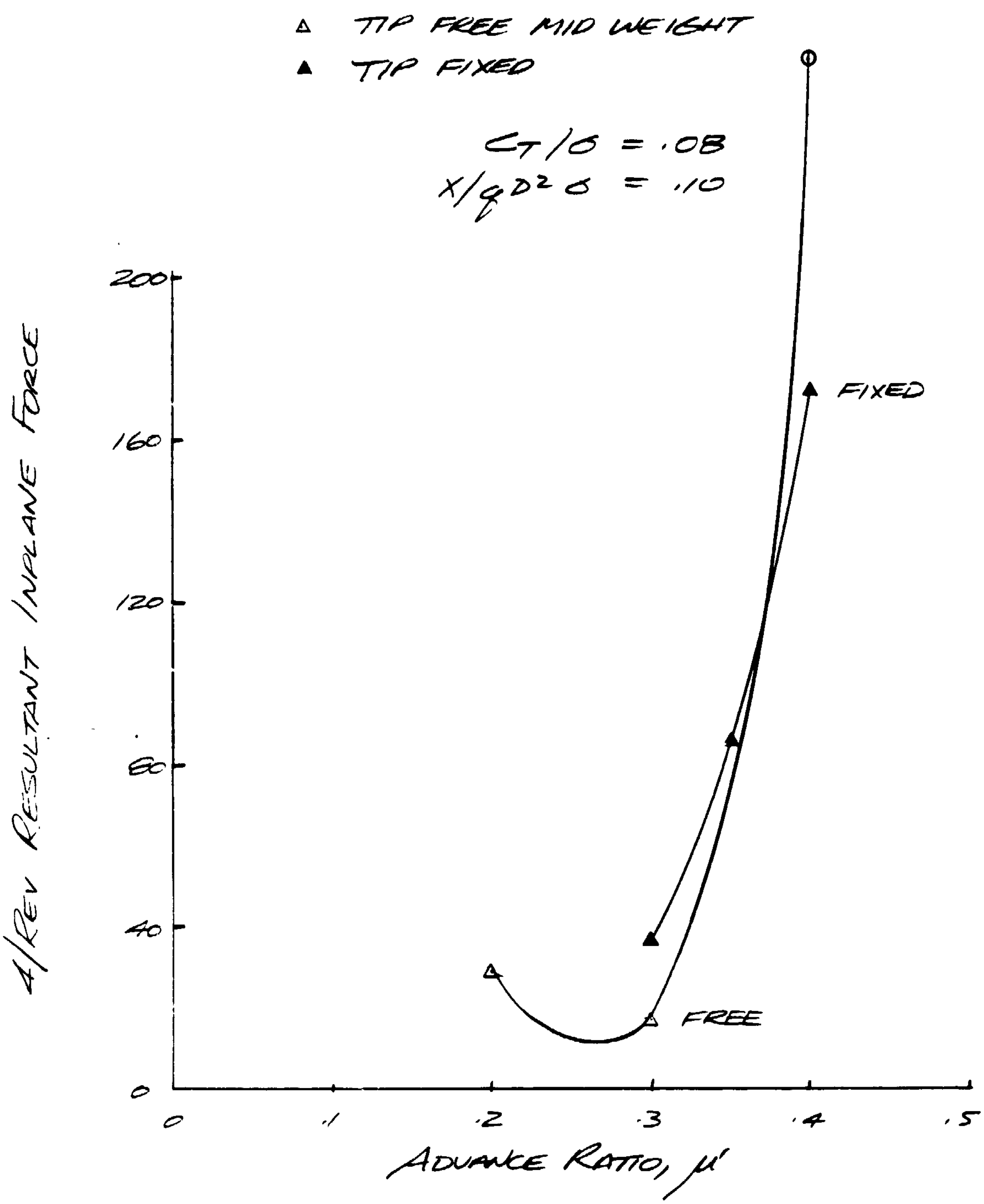
BVWT 271 CONSTANT LIFT TIP



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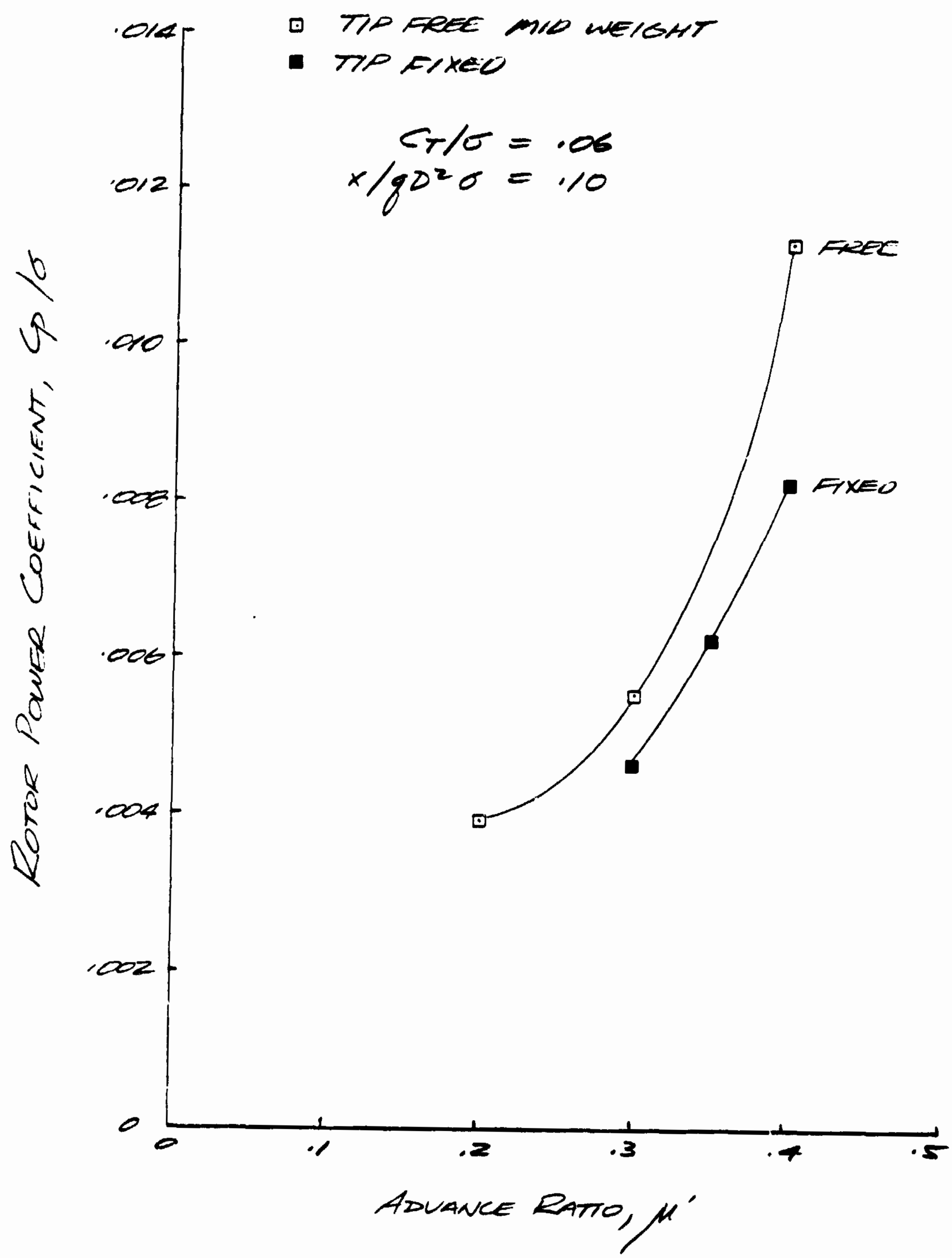
BVWT 271 CONSTANT LIFT TIP



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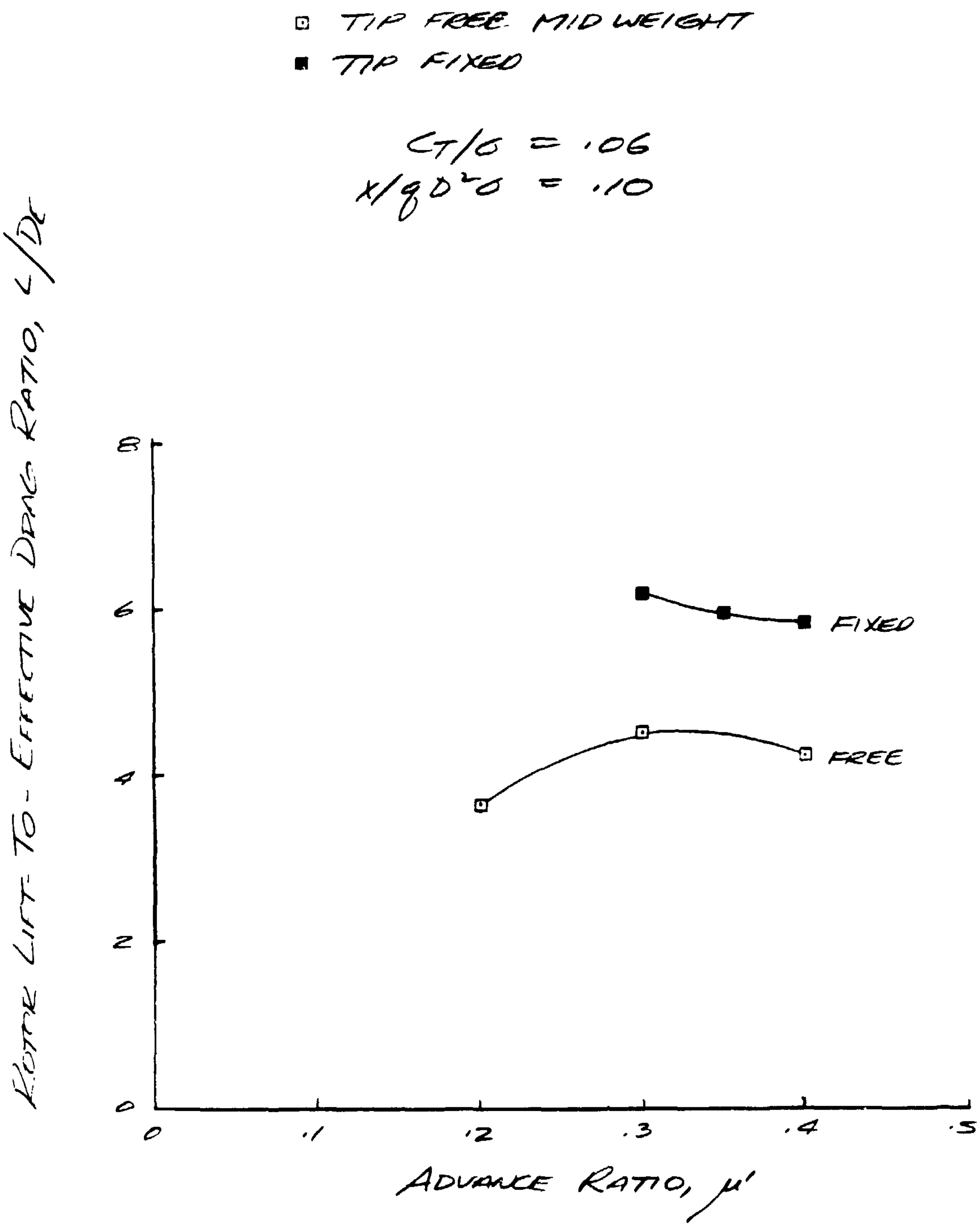
BVWT 271 CONSTANT LIFT TIP



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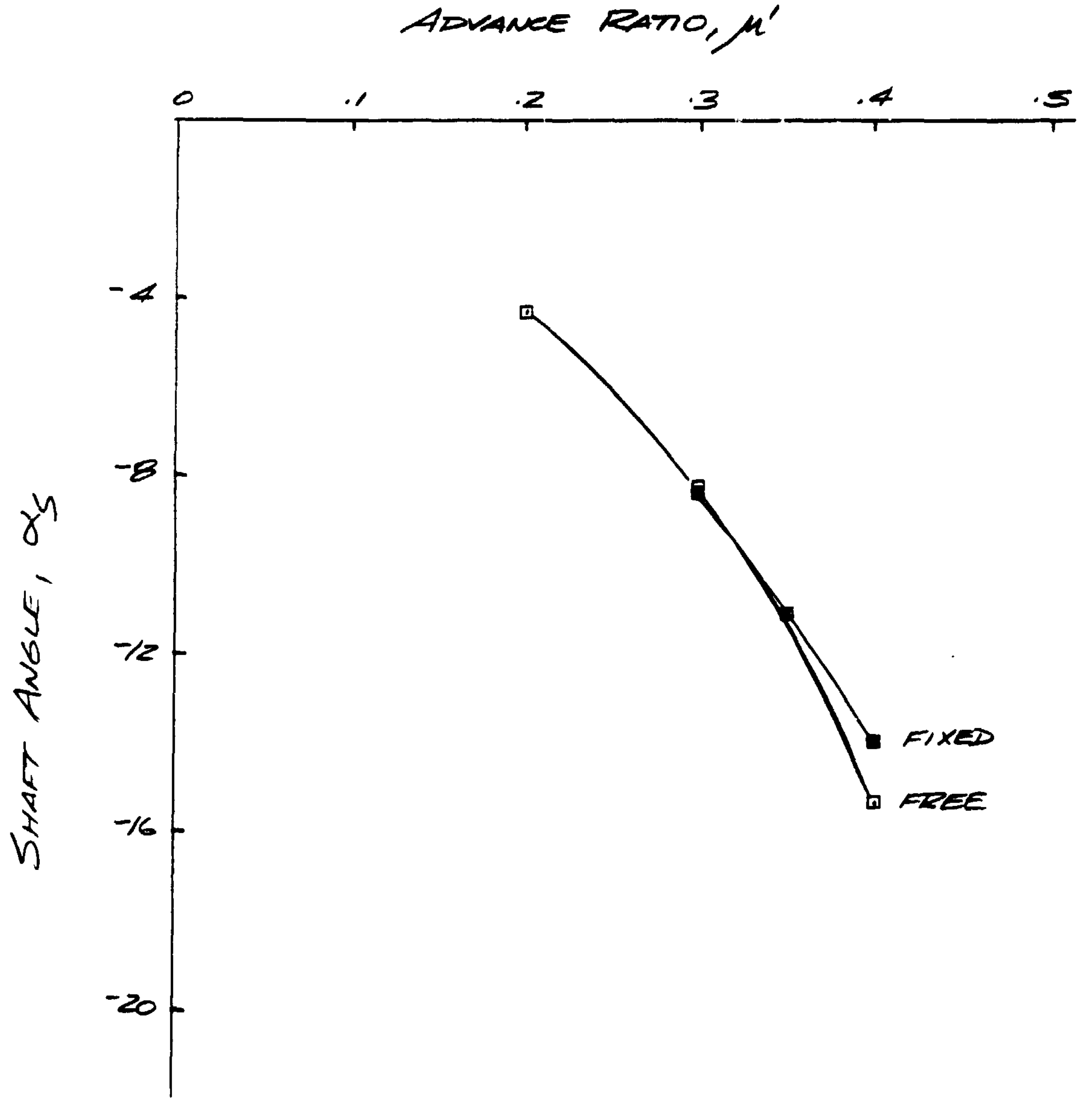
BVWT 271 CONSTANT LIFT TIP

□ TIP FREE MID WEIGHT

■ TIP FIXED

$C_T/\sigma = .06$

$X/qD^2\sigma = .10$



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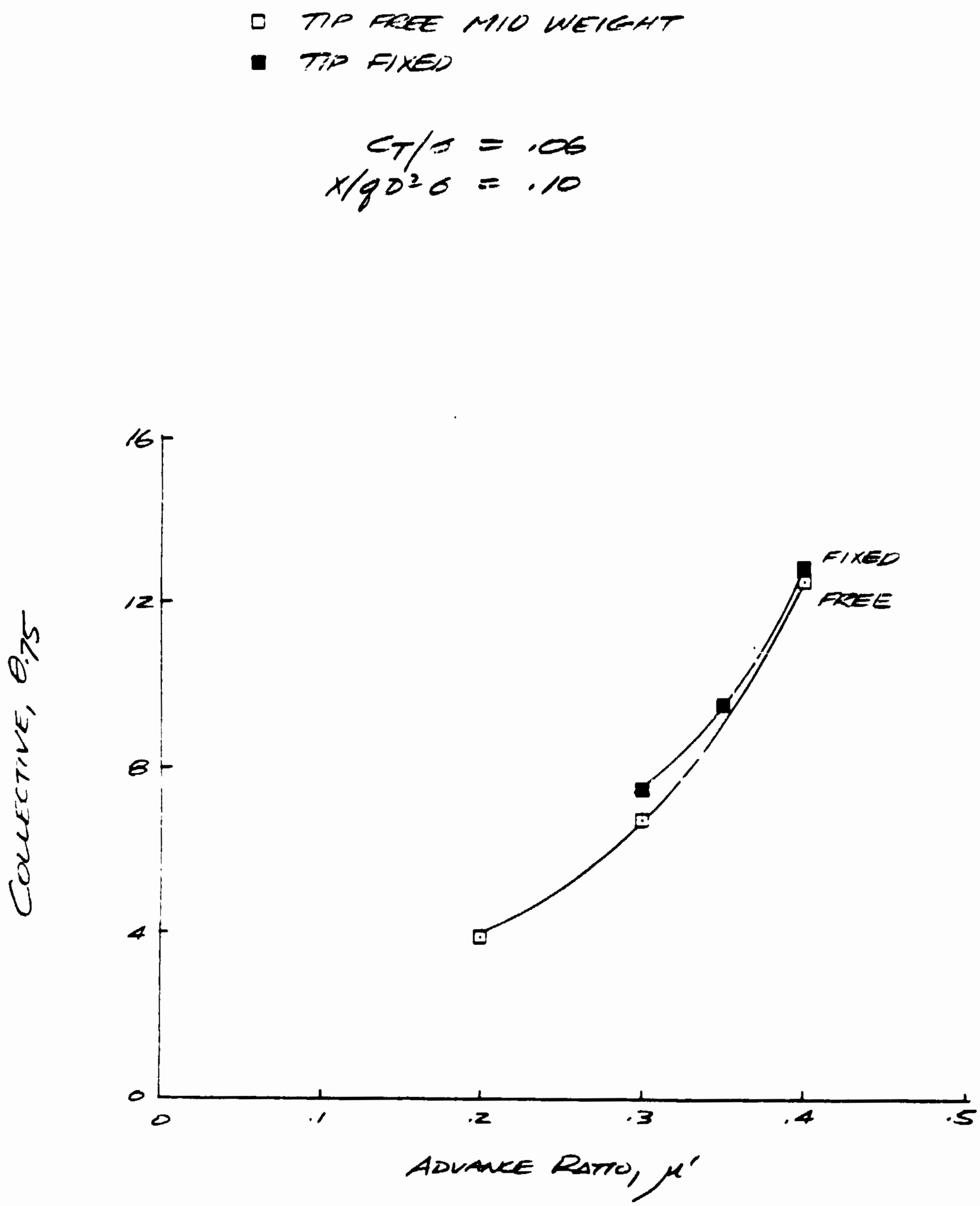
BVWT 271 CONSTANT LIFT TIP



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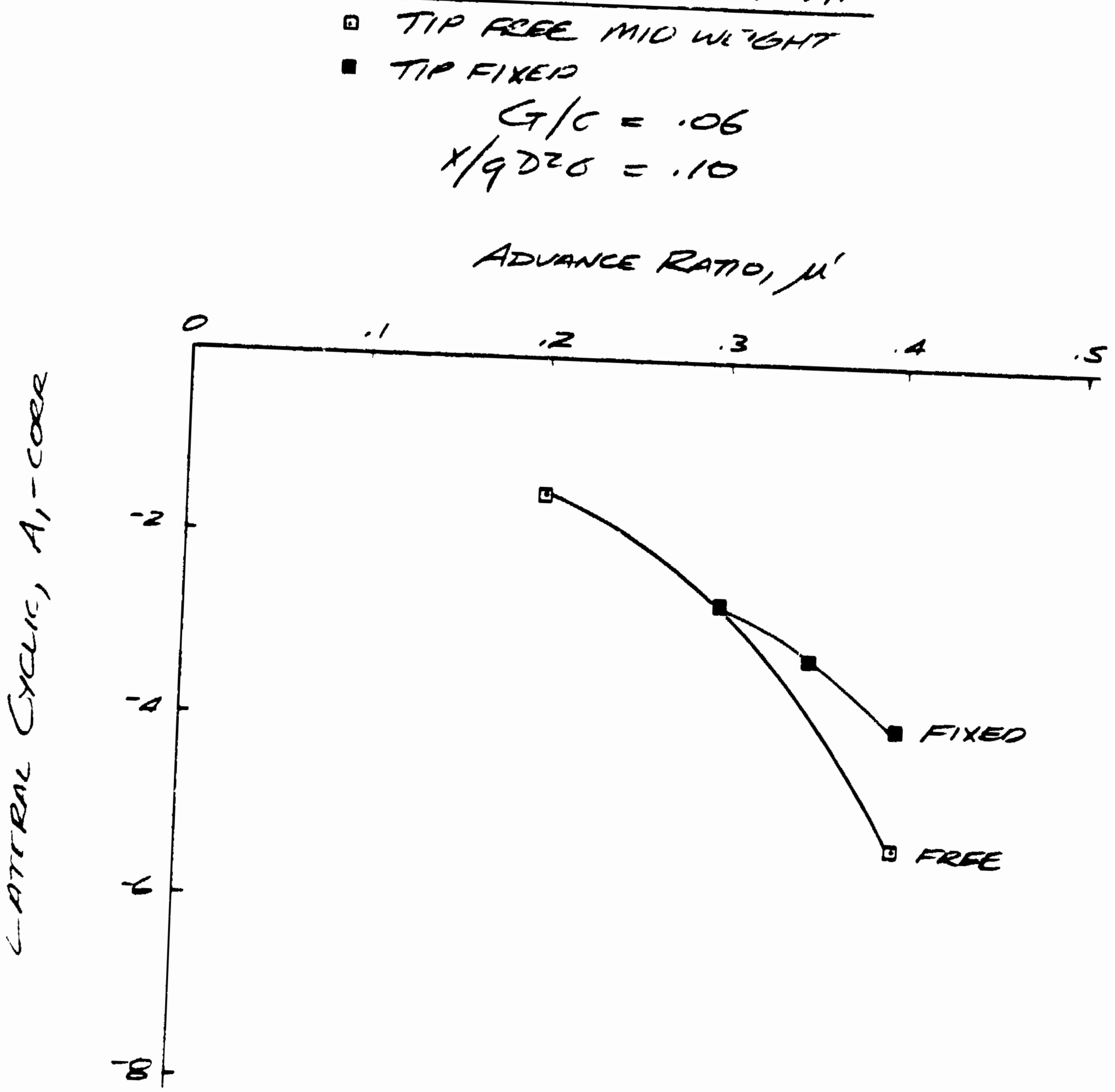
BVWT 271 CONSTANT LIFT TIP



KMO 10/3/81

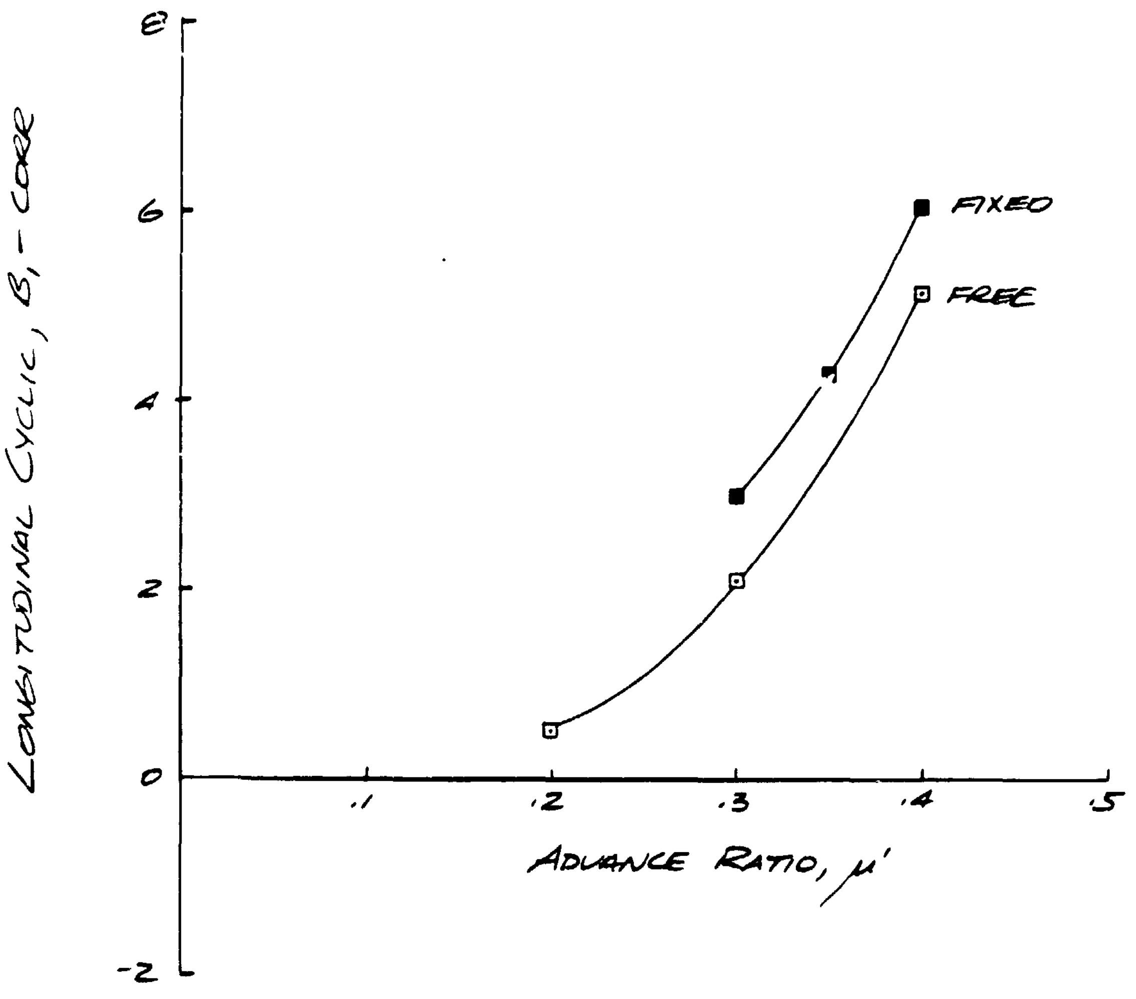
BVWT 271 CONSTANT LIFT TIP

□ TIP FREE MID WEIGHT

■ TIP FIXED

$C_T/\sigma = .06$

$X/qD^2\sigma = .10$



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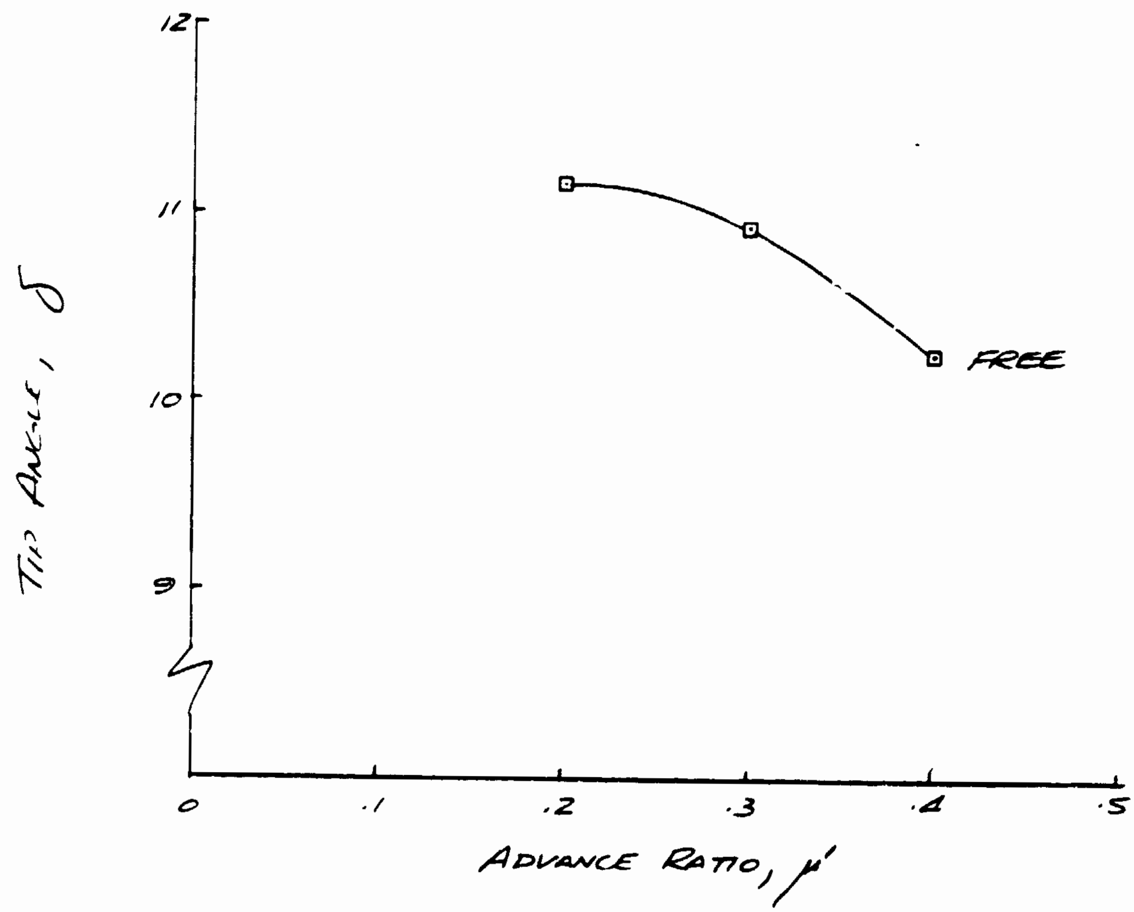
BVWT 271 CONSTANT LIFT TIP

□ TIP FREE MID WEIGHT
(TIP FIXED $\delta = 0$)

$C_T/\sigma = .06$
$X/qD^2\sigma = .10$



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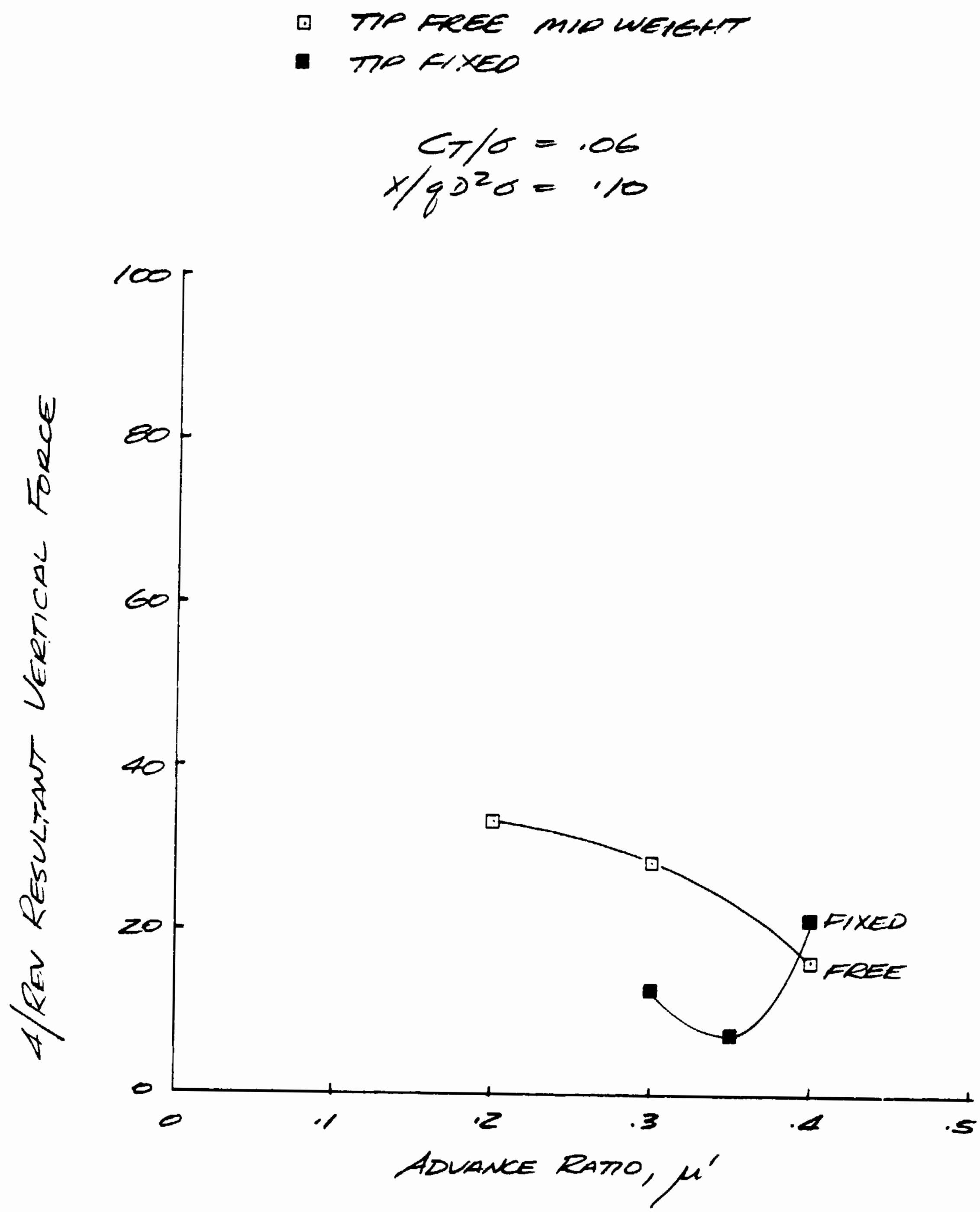
BVWT 271 CONSTANT LIFT TIP



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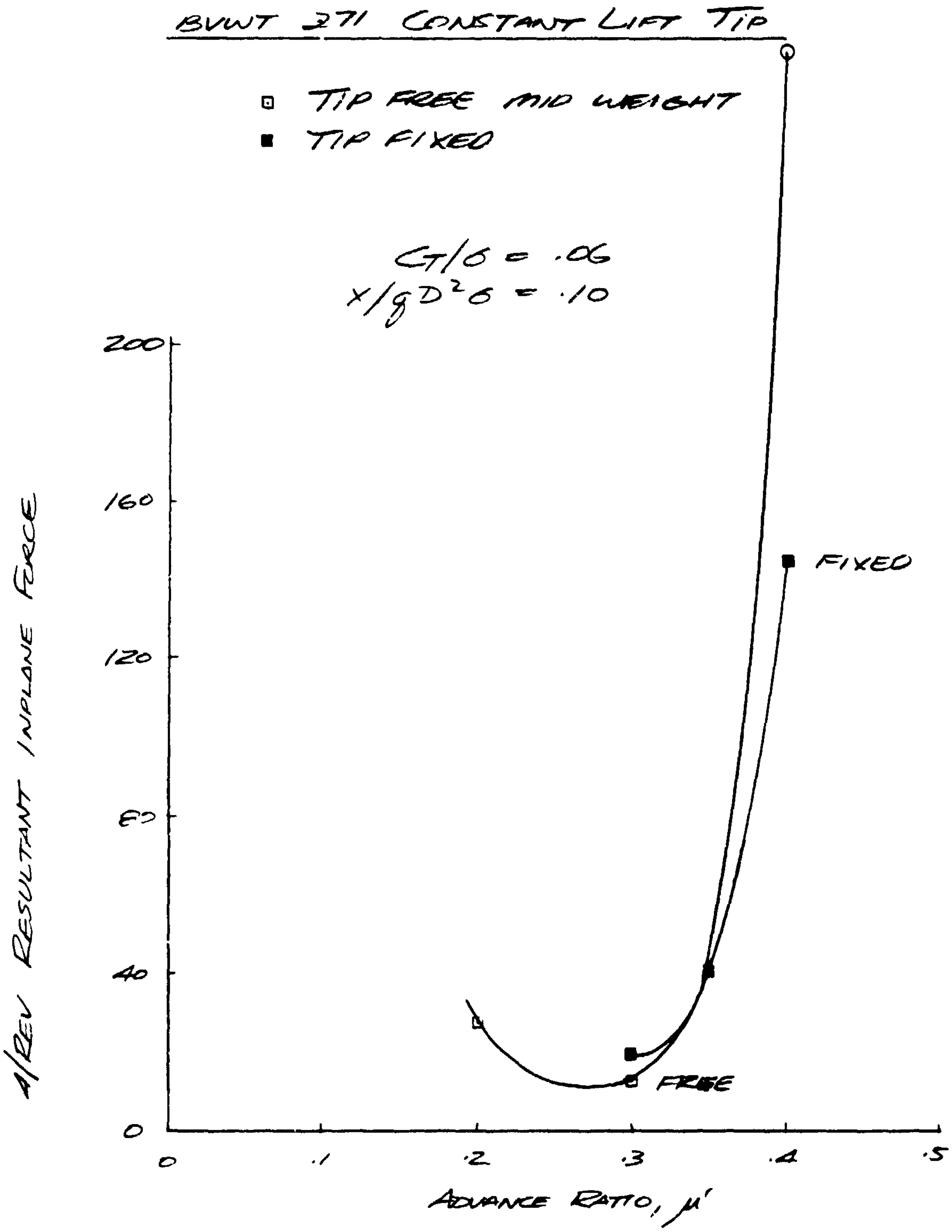

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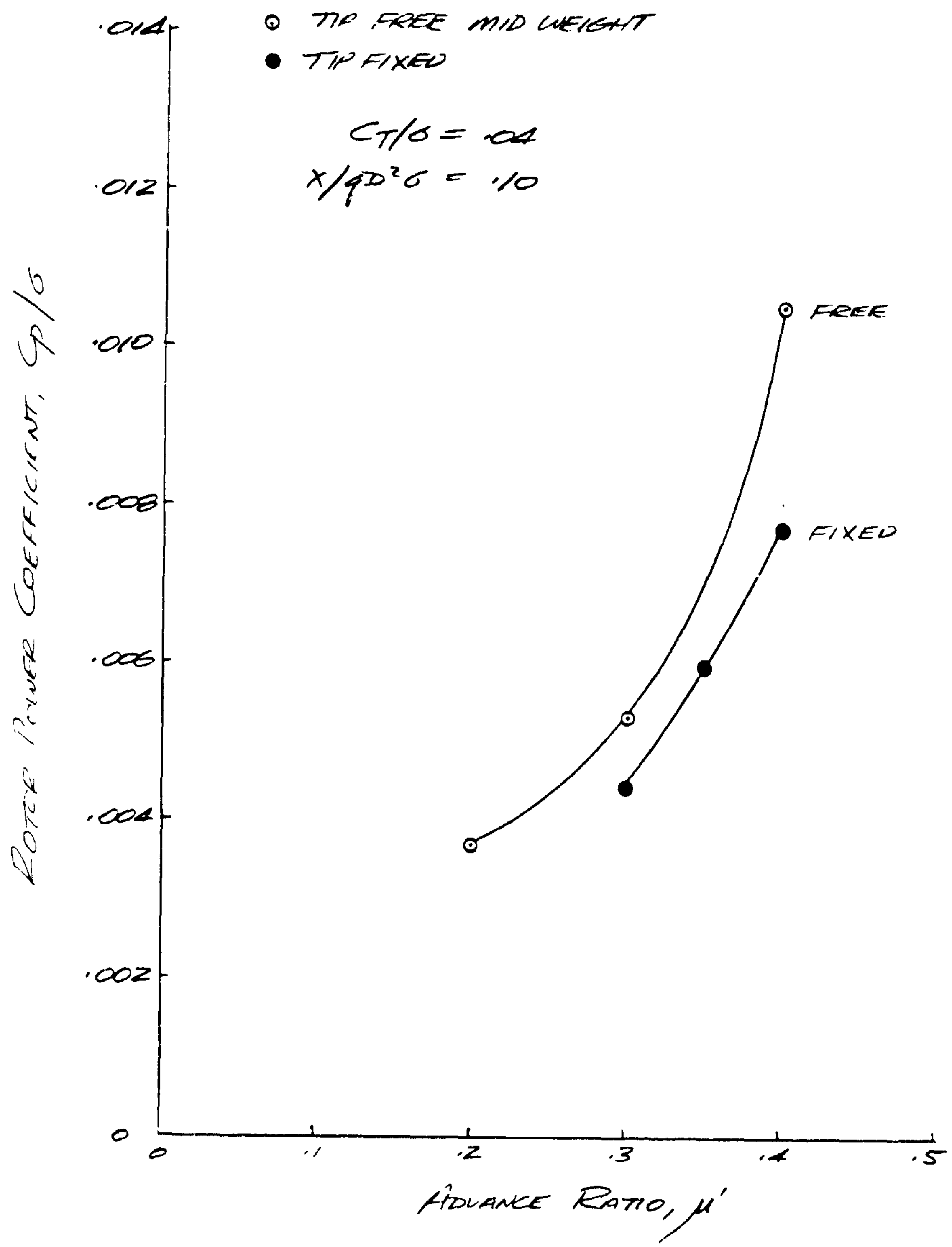
BVWT 271 CONSTANT LIFT TIP



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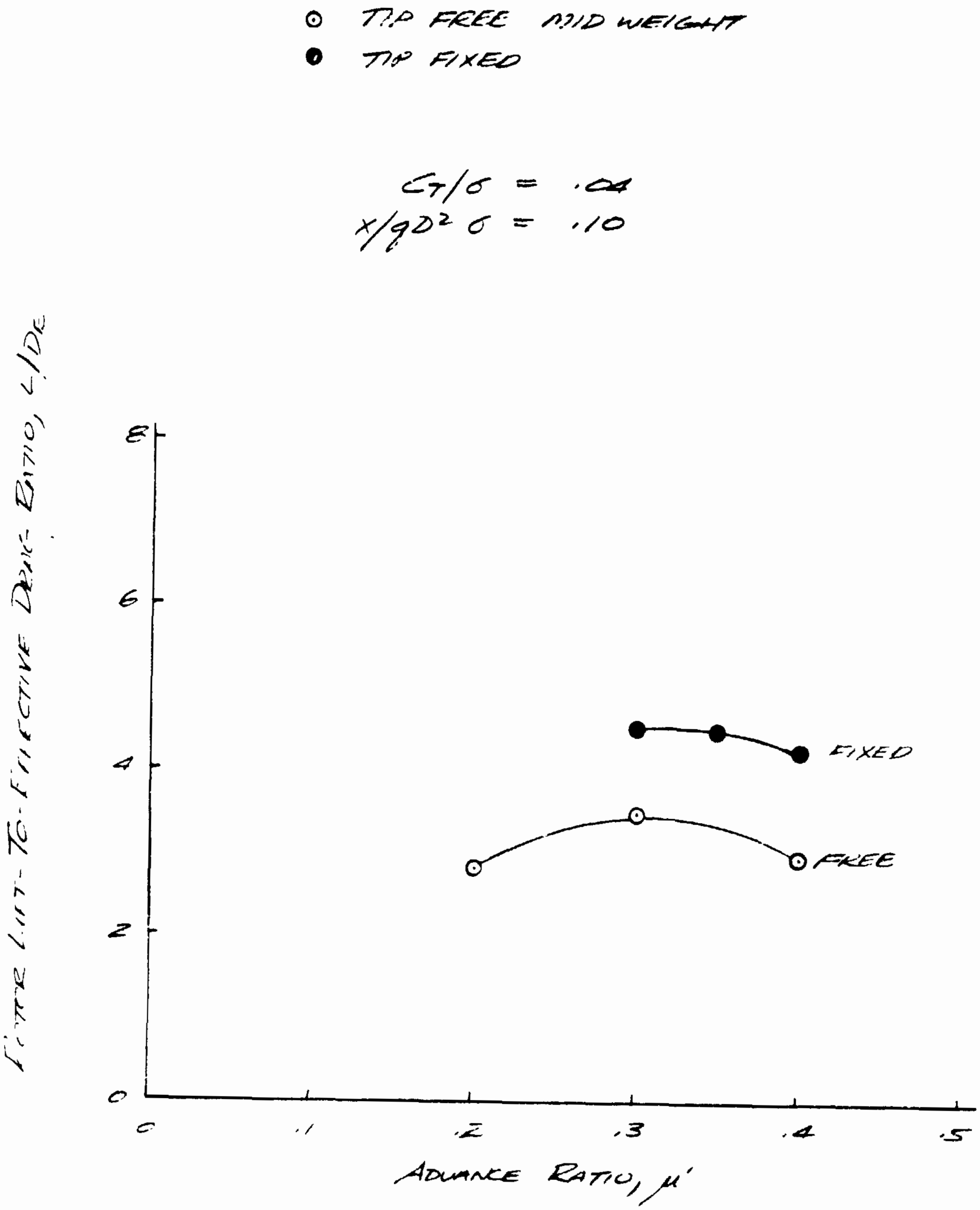
BLUT 271 CONSTANT LIFT TIP



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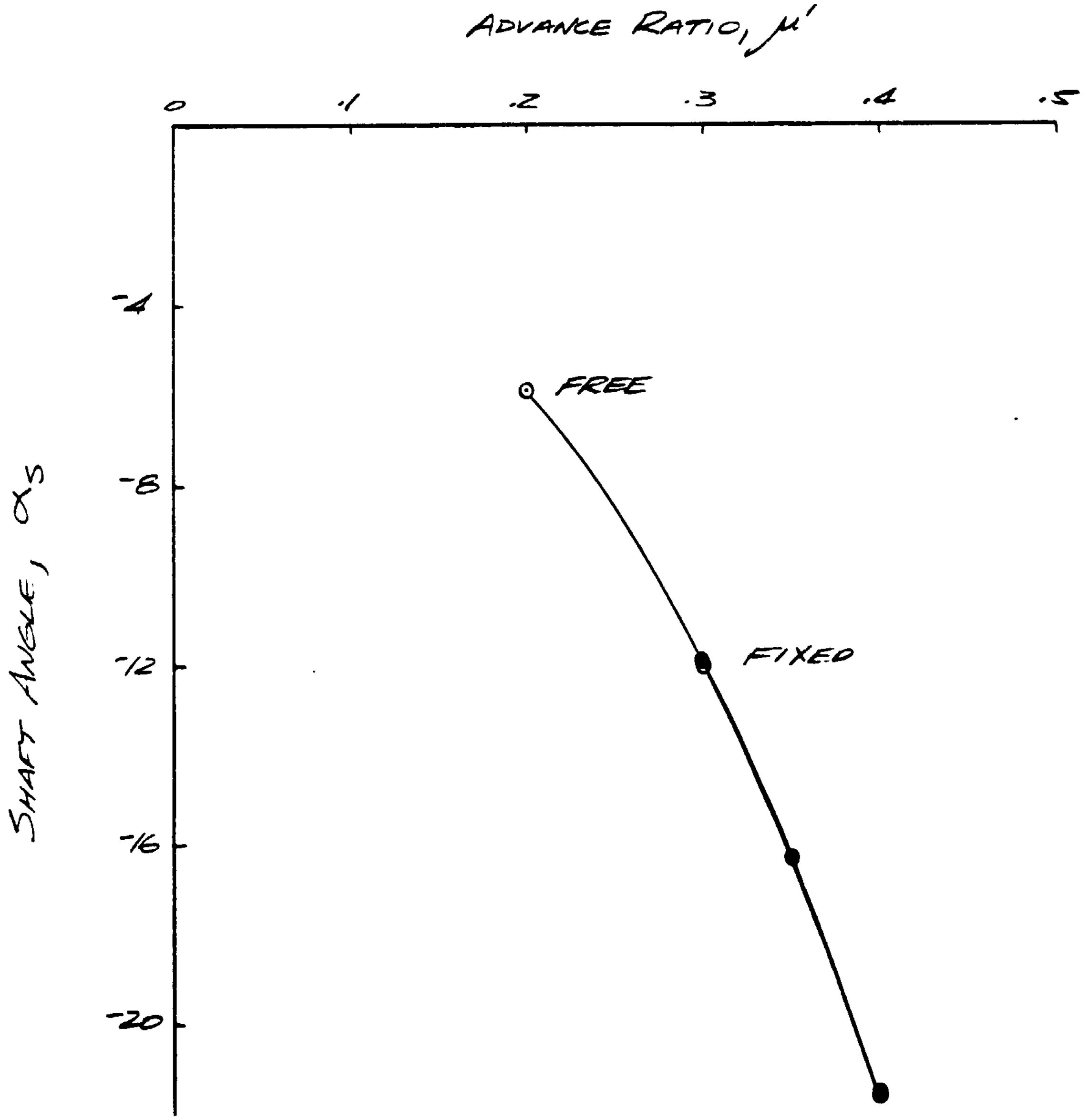
BVWT 271 CONSTANT LIFT TIP

⊙ TIP FREE MID WEIGHT

● TIP FIXED

$C_T/\sigma = .04$

$X/qD^2\sigma = .10$

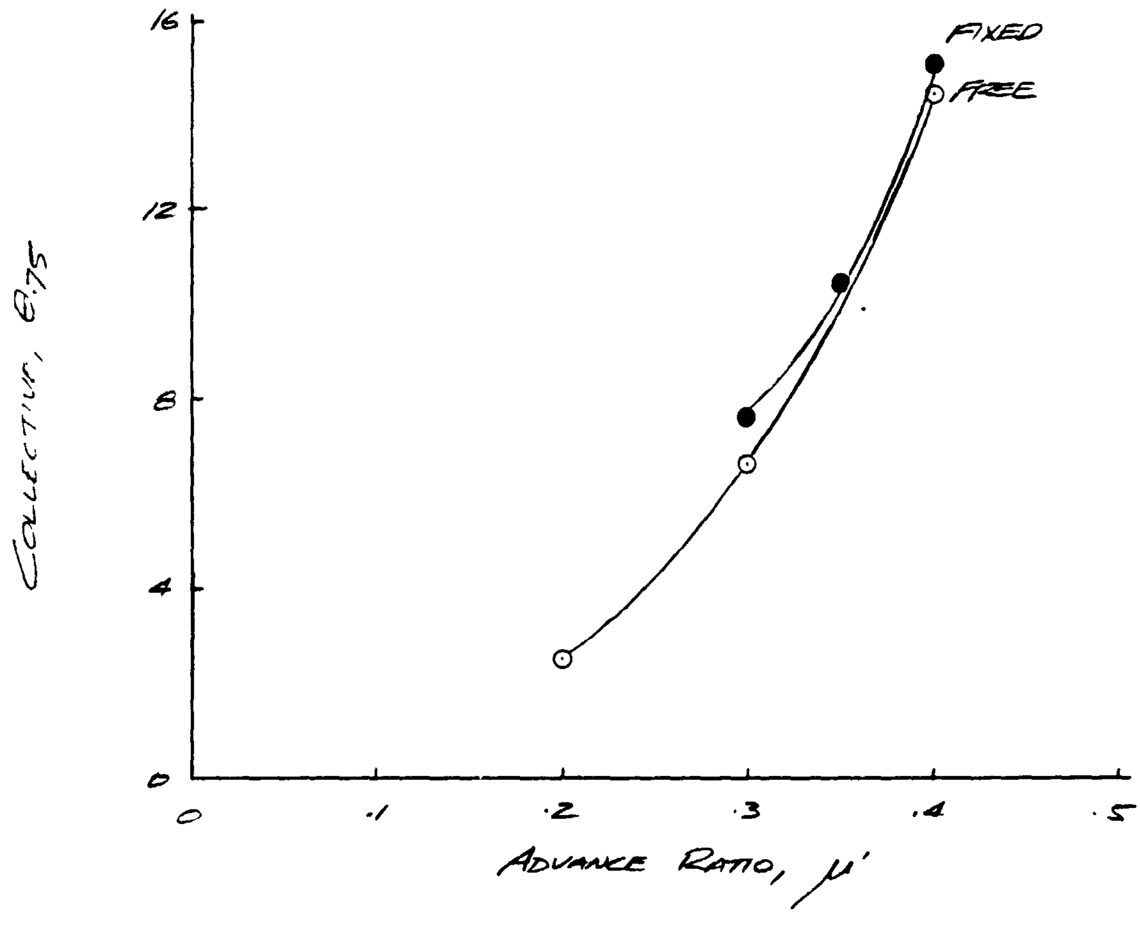


KMB 10/9/61

BVWT 271 CONSTANT LIFT TIP

○ TIP FREE MID WEIGHT
● TIP FIXED

$C_T/\sigma = .04$
$X/qD^2\sigma = .10$



KMB 10/9/81

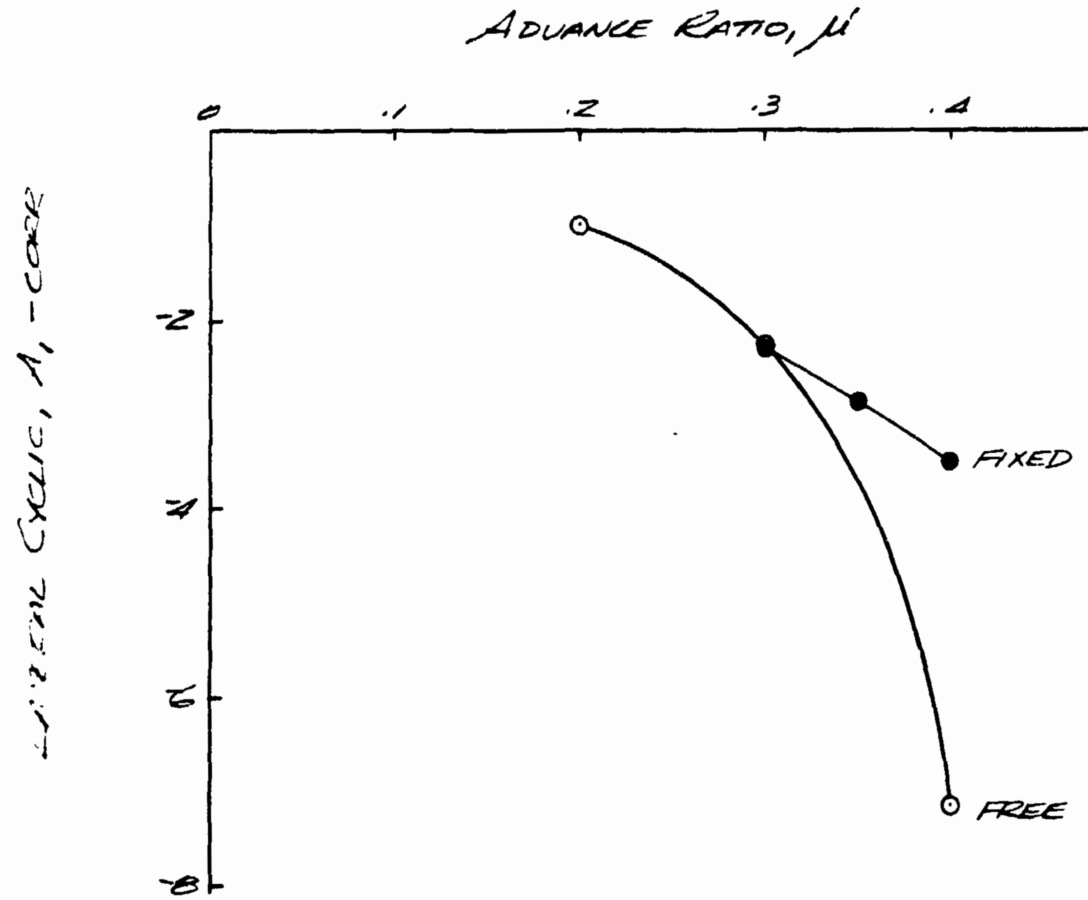
BVWT 271 CONSTANT LIFT TIP

○ TIP FREE MID WEIGHT

● TIP FIXED

$C_T/\sigma = .08$

$X/qD^2\sigma = .10$



KMB 10/9/81

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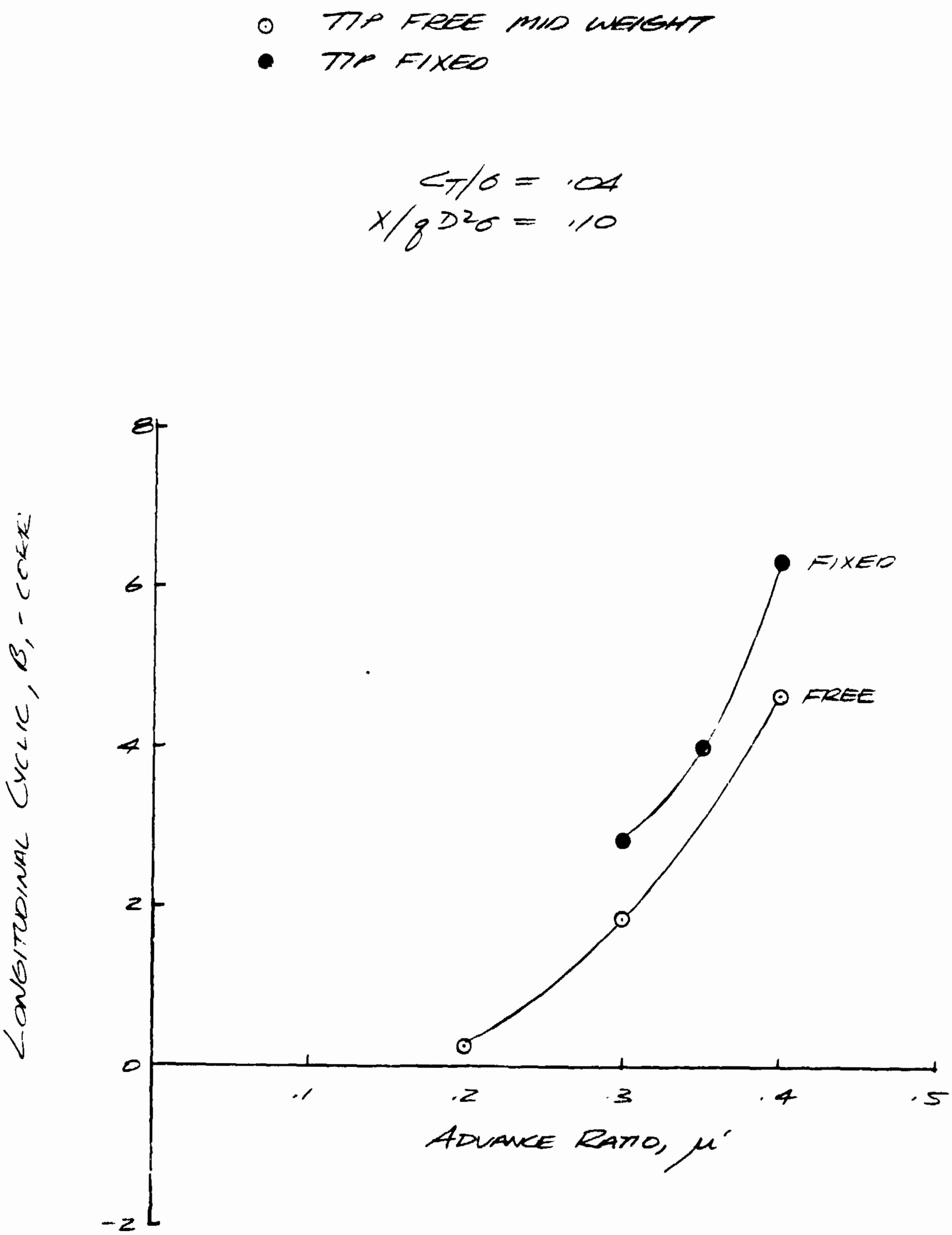
BVWT 271 CONSTANT LIFT TIP

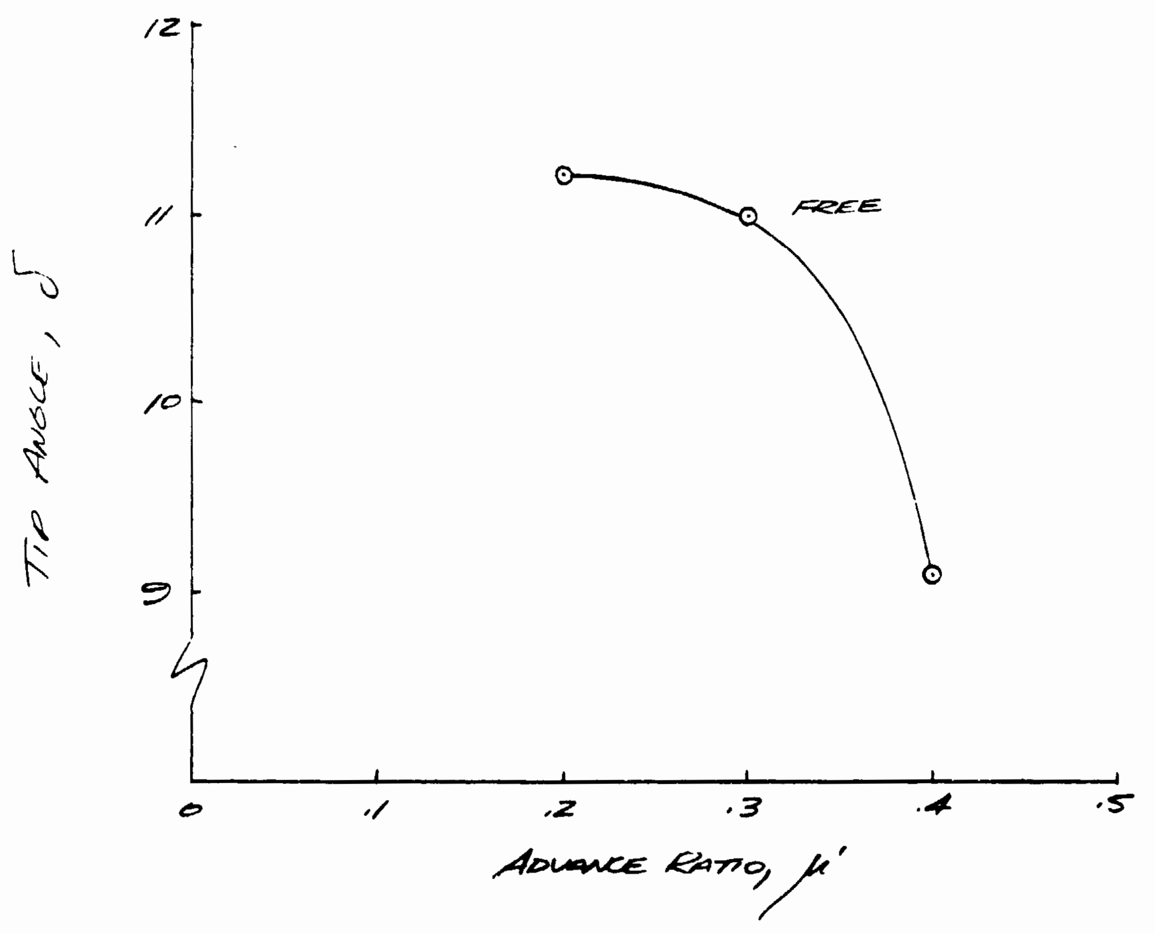


KMC 10/5/81

BVWT 271 CONSTANT LIFT TIP

⊙ TIP FREE MID WEIGHT
(TIP FIXED $\delta = 0$)

$C_T/\sigma = .04$
$X/qD^2\sigma = .10$



KMCS 10/9/81

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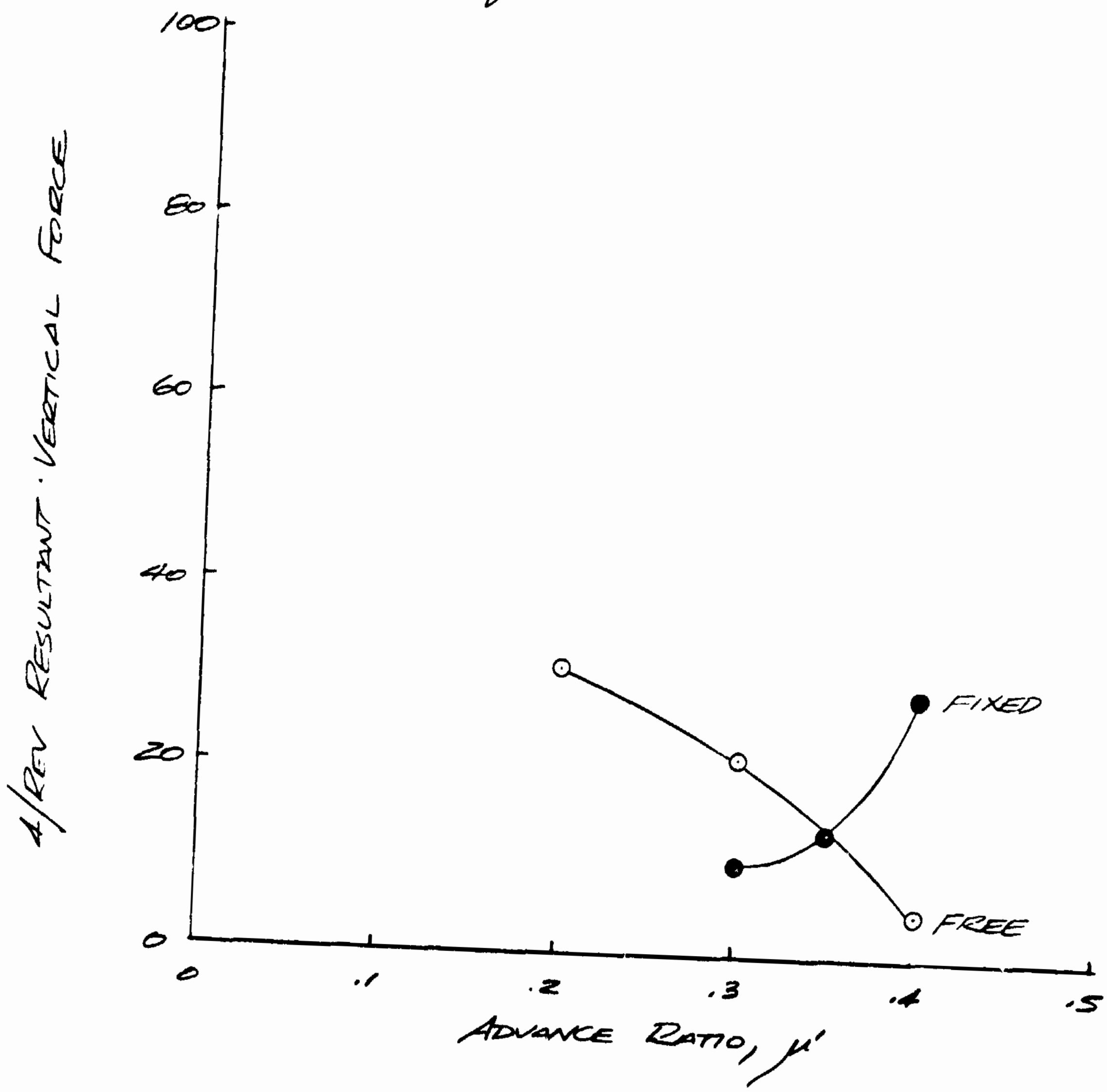
BVWT 271 CONSTANT LIFT TIP

○ TIP FREE MID WEIGHT
● TIP FIXED

$C_T/\sigma = .04$
$X/qD^2\sigma = .10$



KMB 10/9/81

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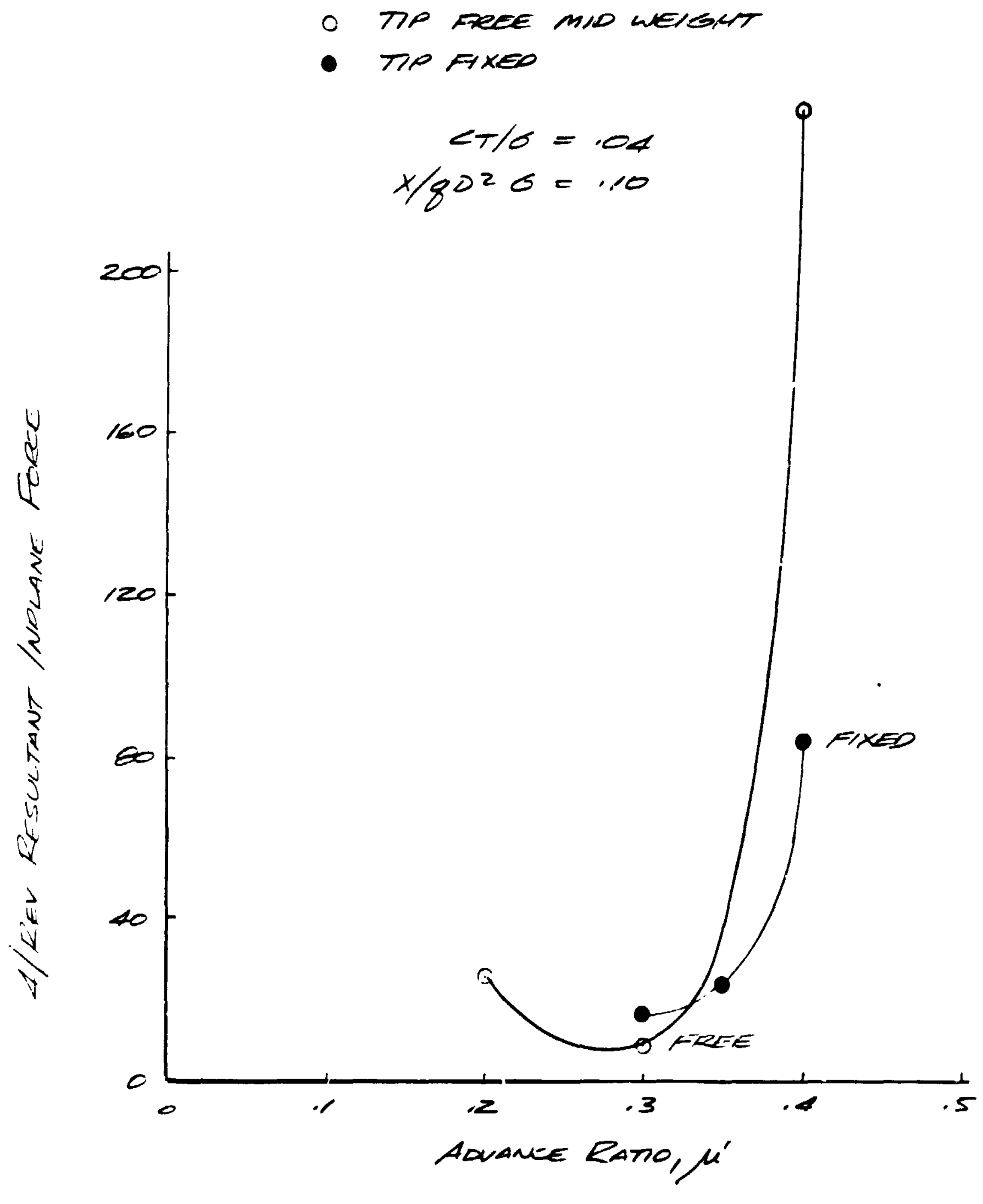
BVWT 271 CONSTANT LIFT TIP



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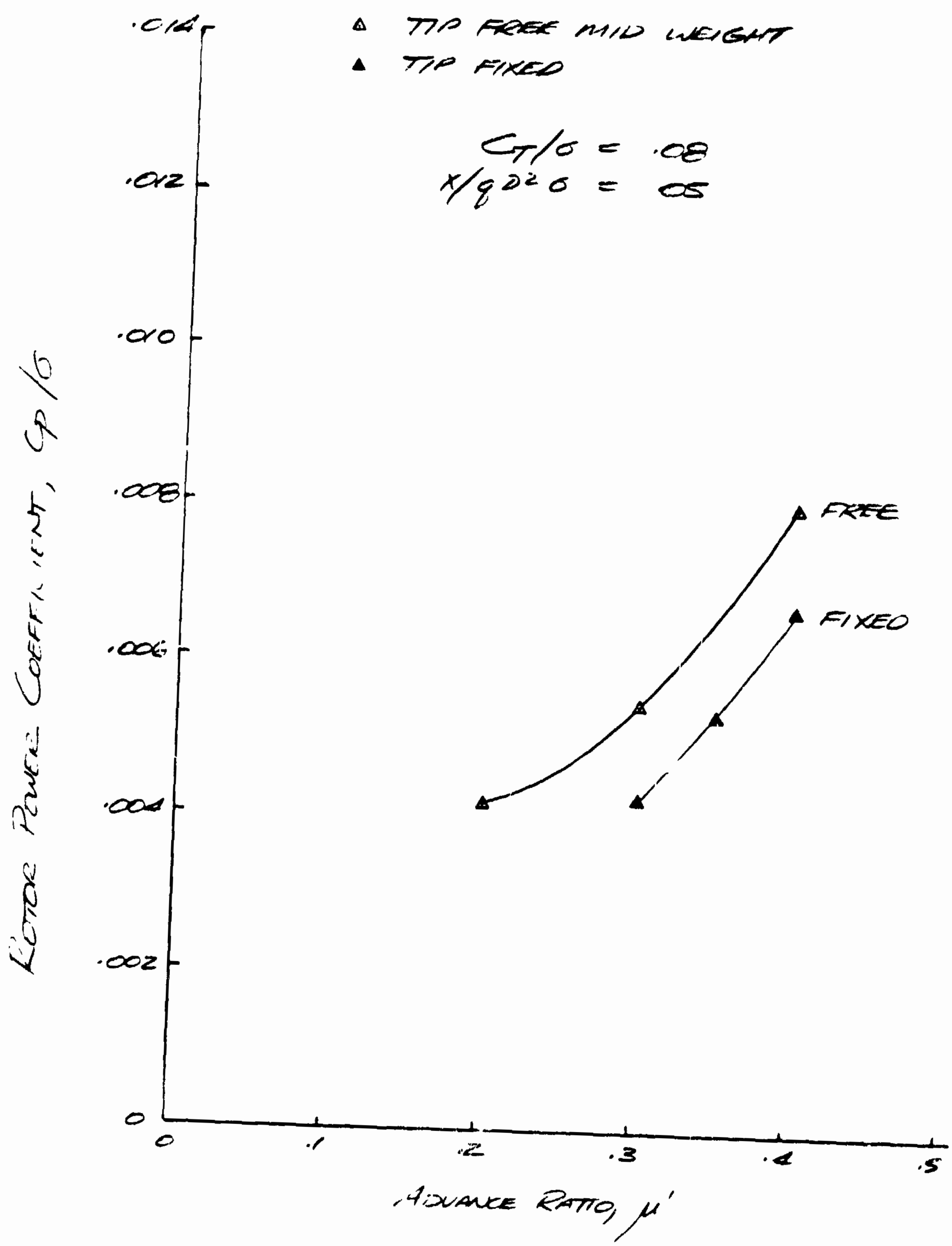

KMB 12/3/81

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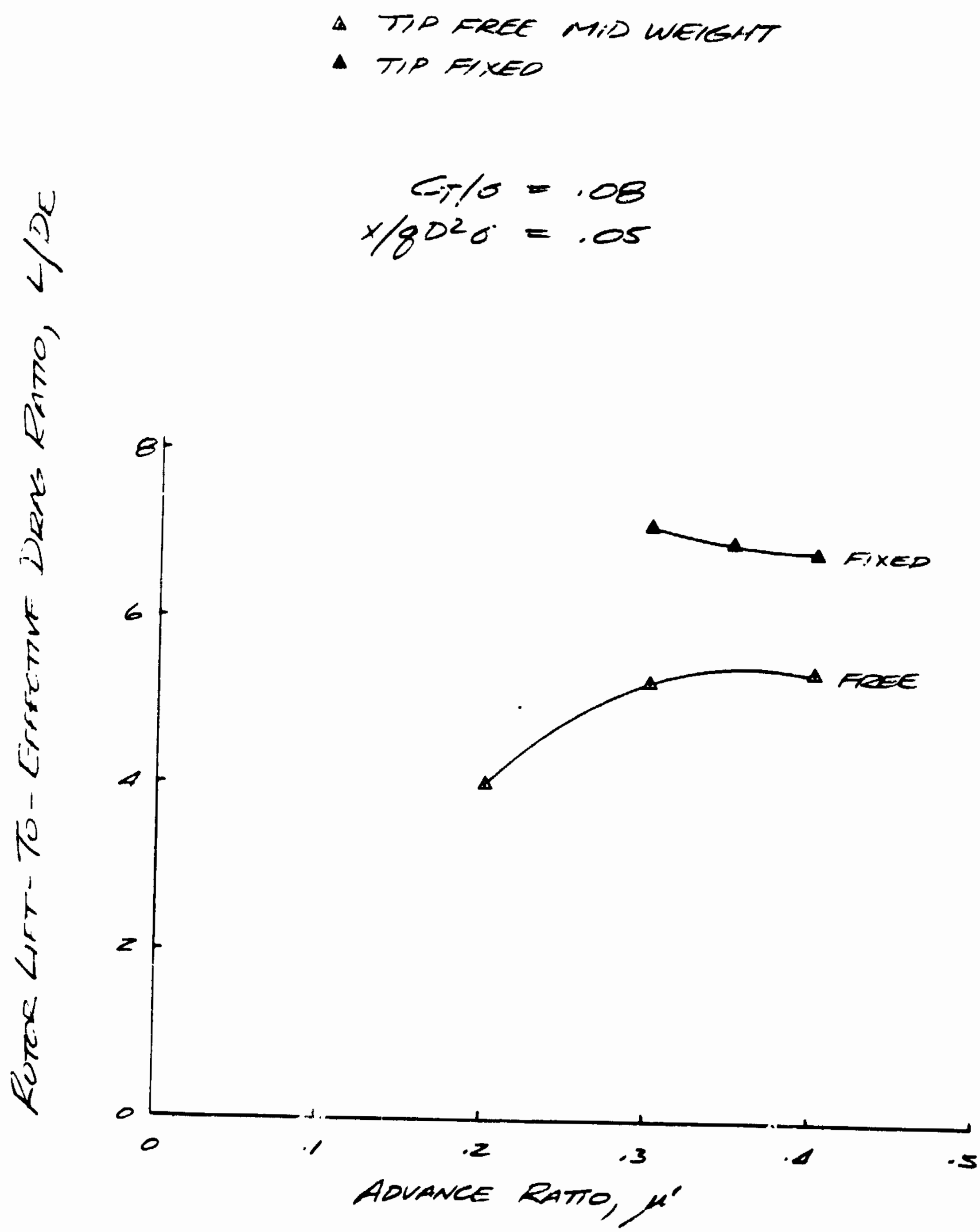
EVWT 271 CONSTANT LIFT TIP



KMB 10/9/81

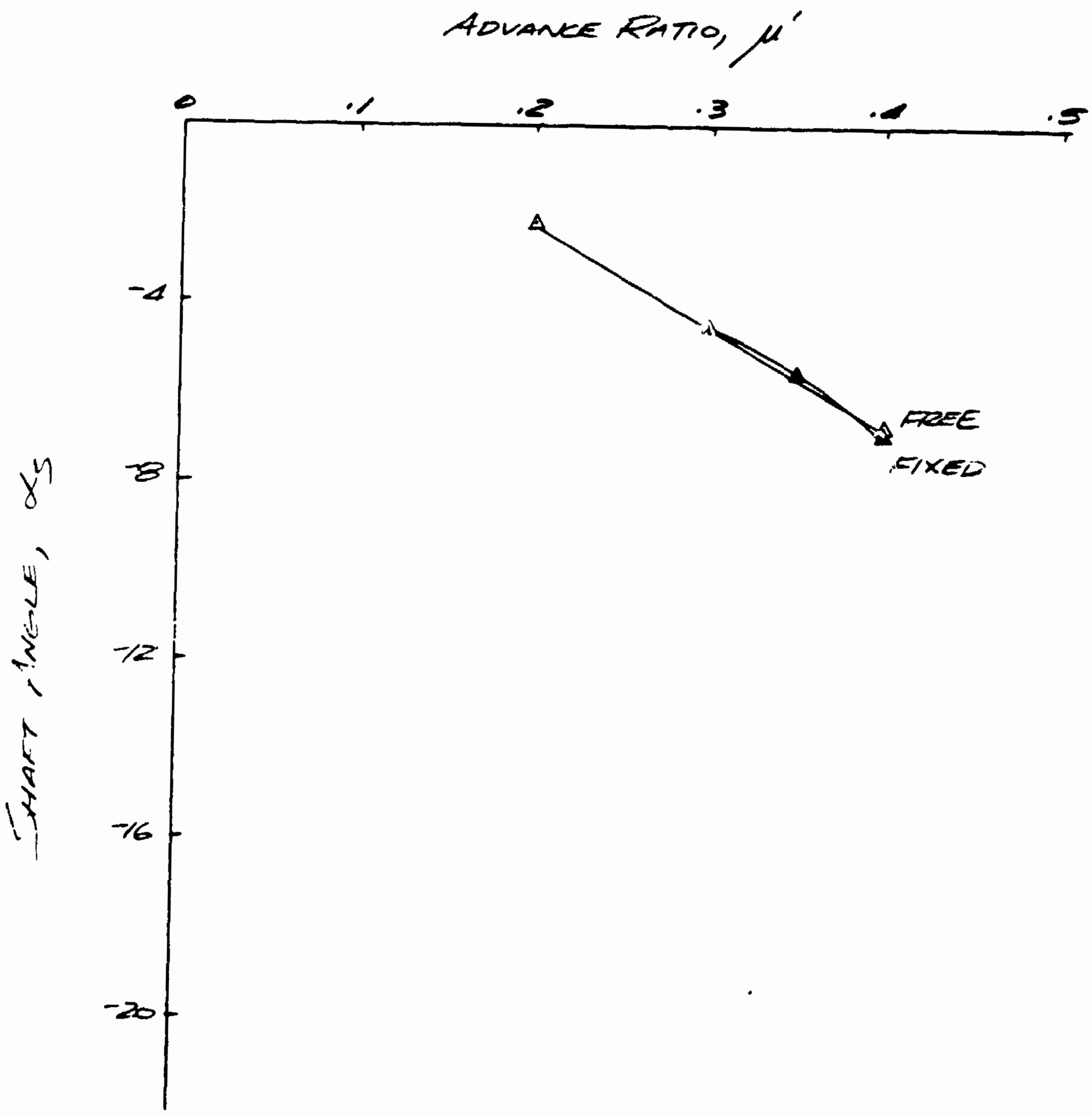
COUNT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT

▲ TIP FIXED

$C_T/\sigma = .08$

$X/qD^2\sigma = .05$



KMB 10/9/81

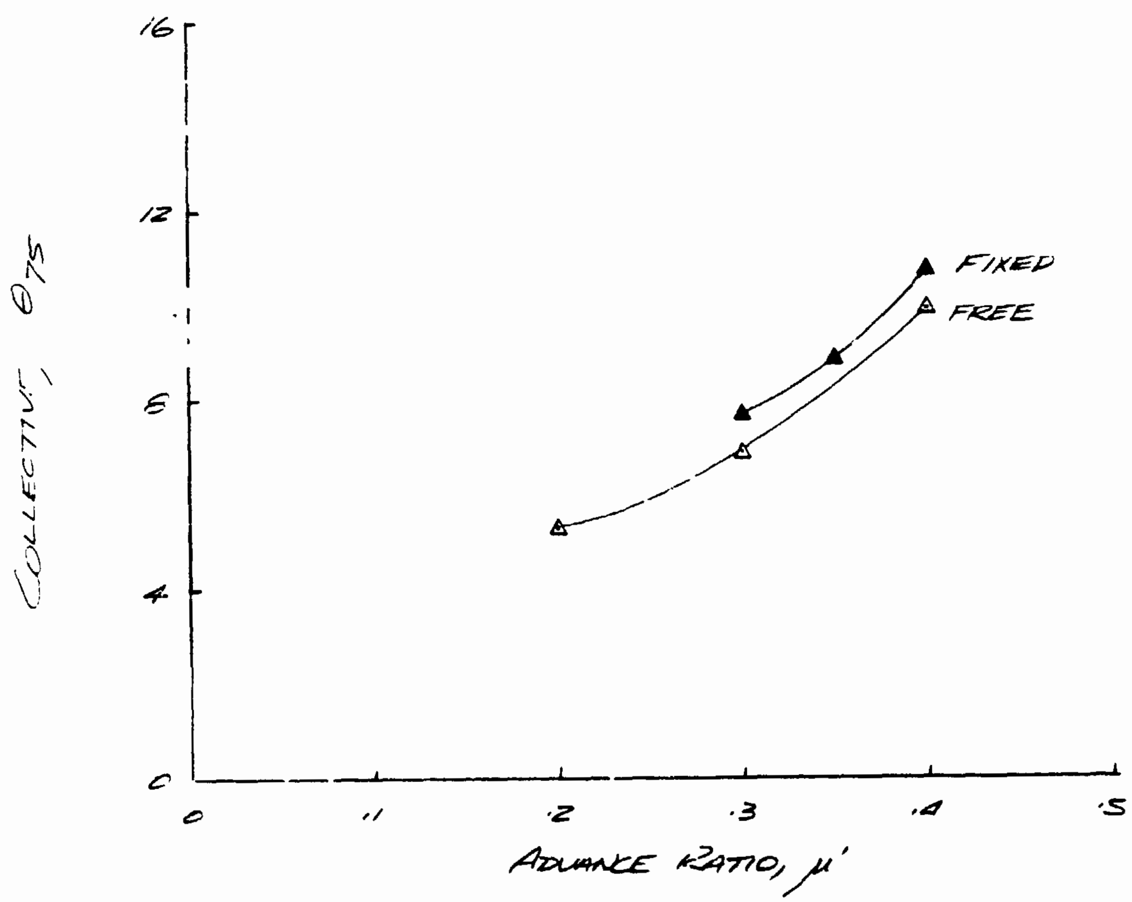
BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT

▲ TIP FIXED

$C_T/\sigma = .08$

$X/qD^2\sigma = .05$



KMB 10/2/81

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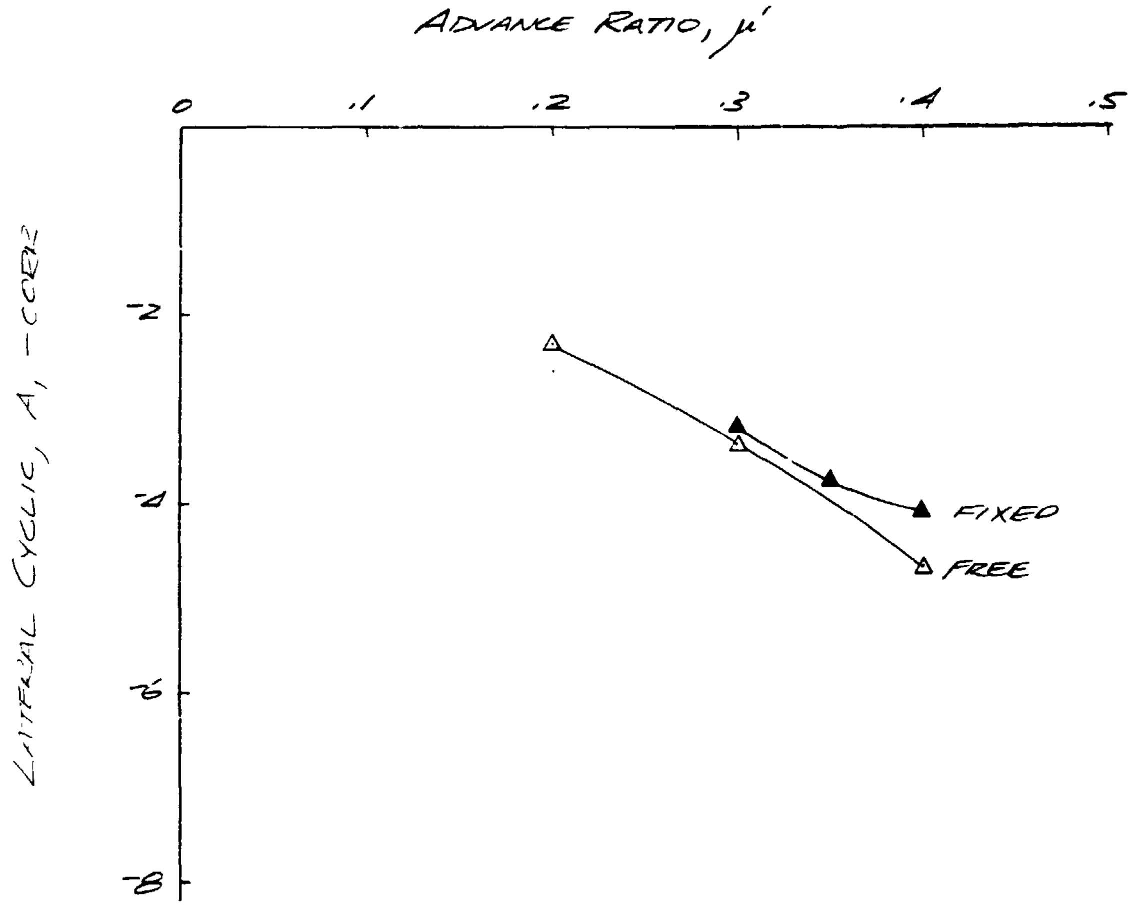
BVWT 271 CONSTANT LIFT TIP

TIP FREE MID WEIGHT
TIP FIXED
$C_T/\sigma = .08$
$X/q D^2 \sigma = .05$



KMB 10/9/81

BVWT Z71 CONSTANT LIFT TIP

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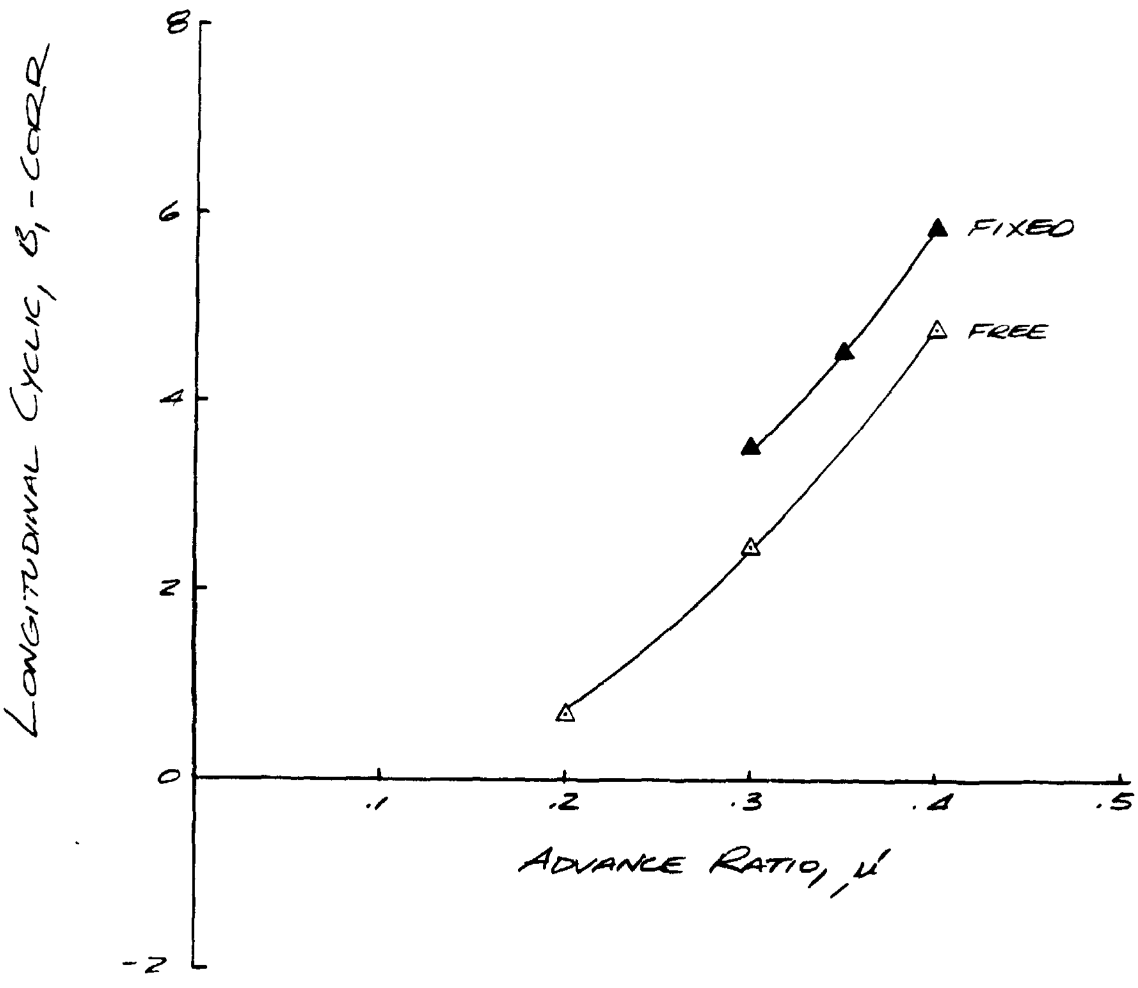
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = .05$



KMB 10/9/81

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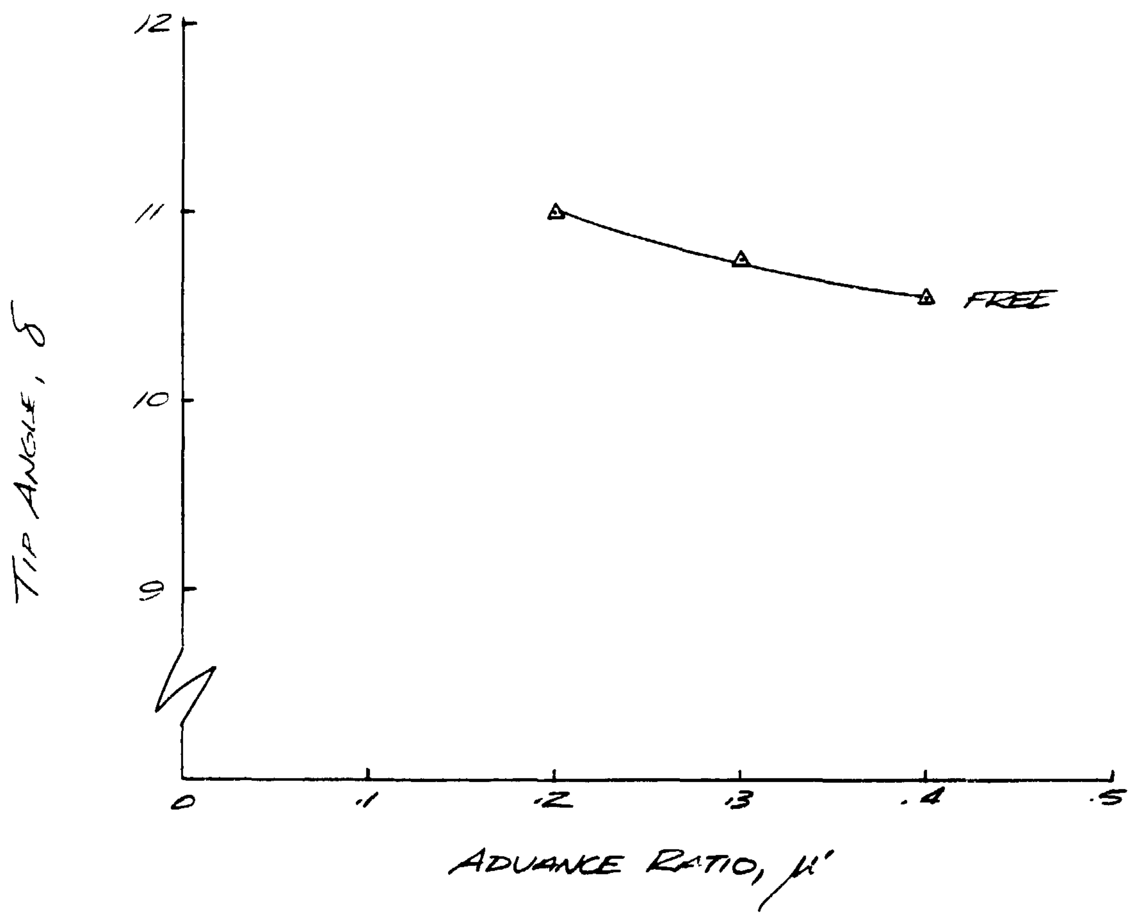
EVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
(TIP FIXED $\delta = 0$)

$C_T/\sigma = .08$
$X/qD^2\sigma = .05$



KMB 10/9/81

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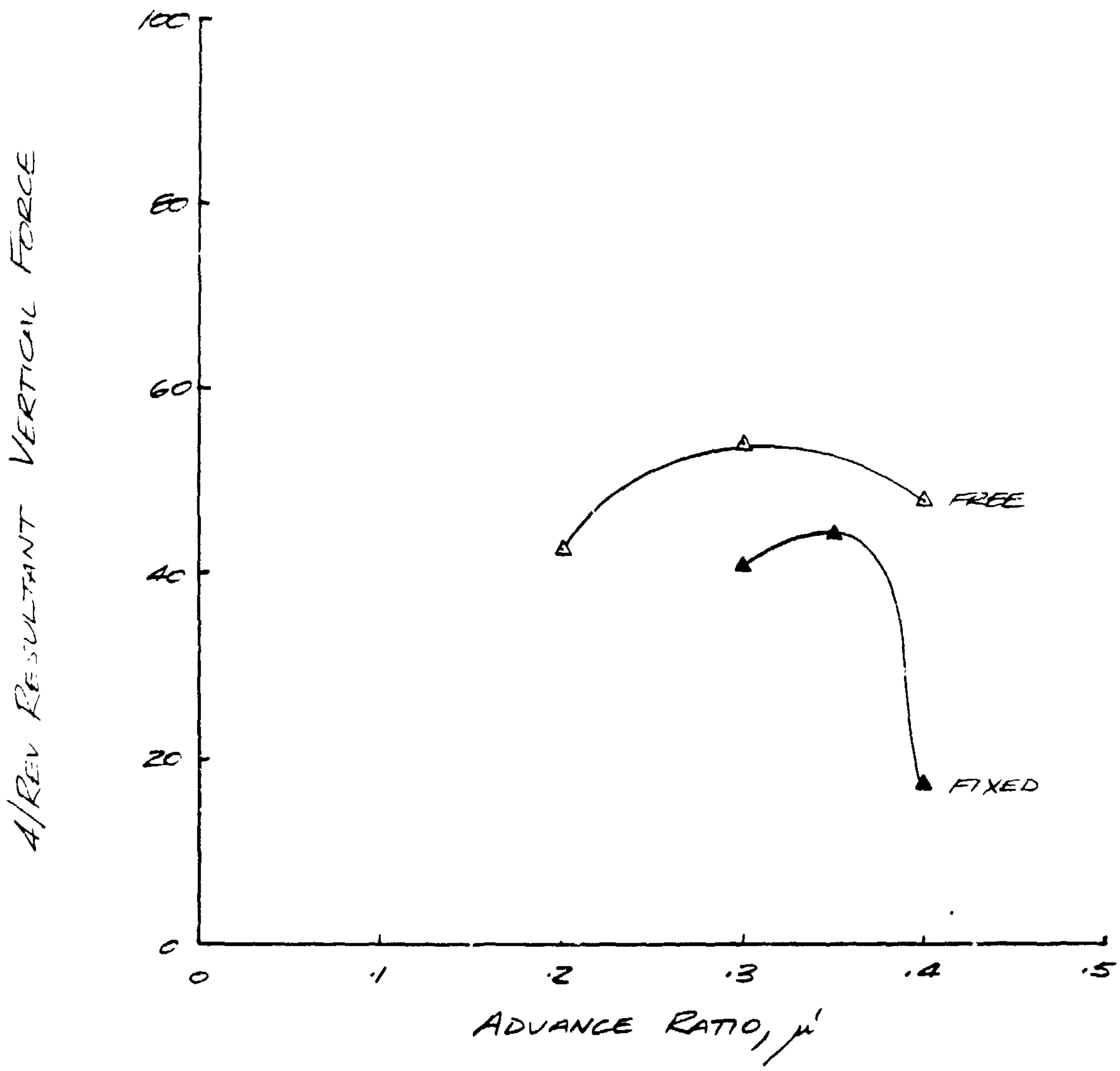
EVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = .05$

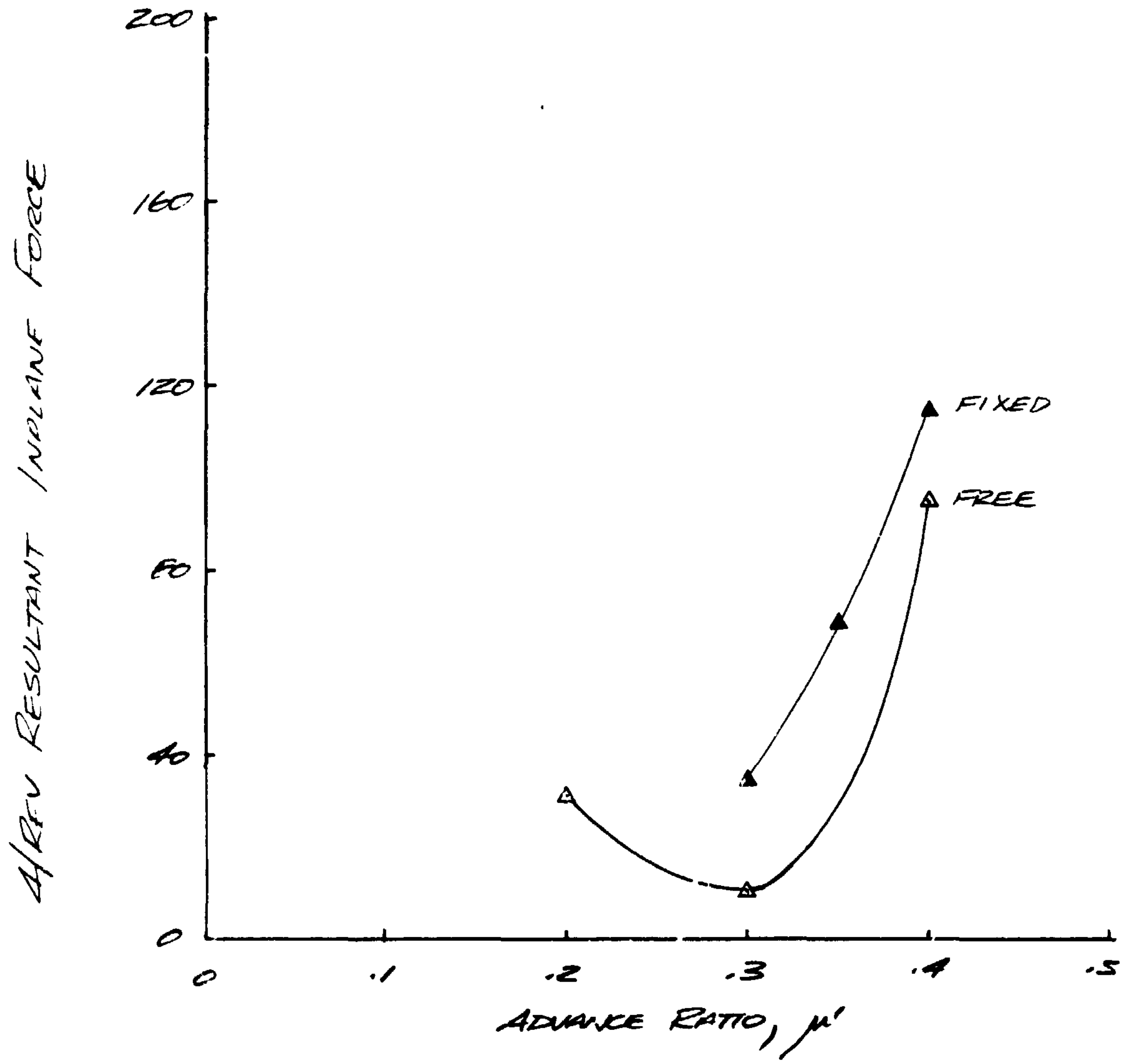


KMB 10/2/81

BVWT 271 CONSTANT LIFT TIP

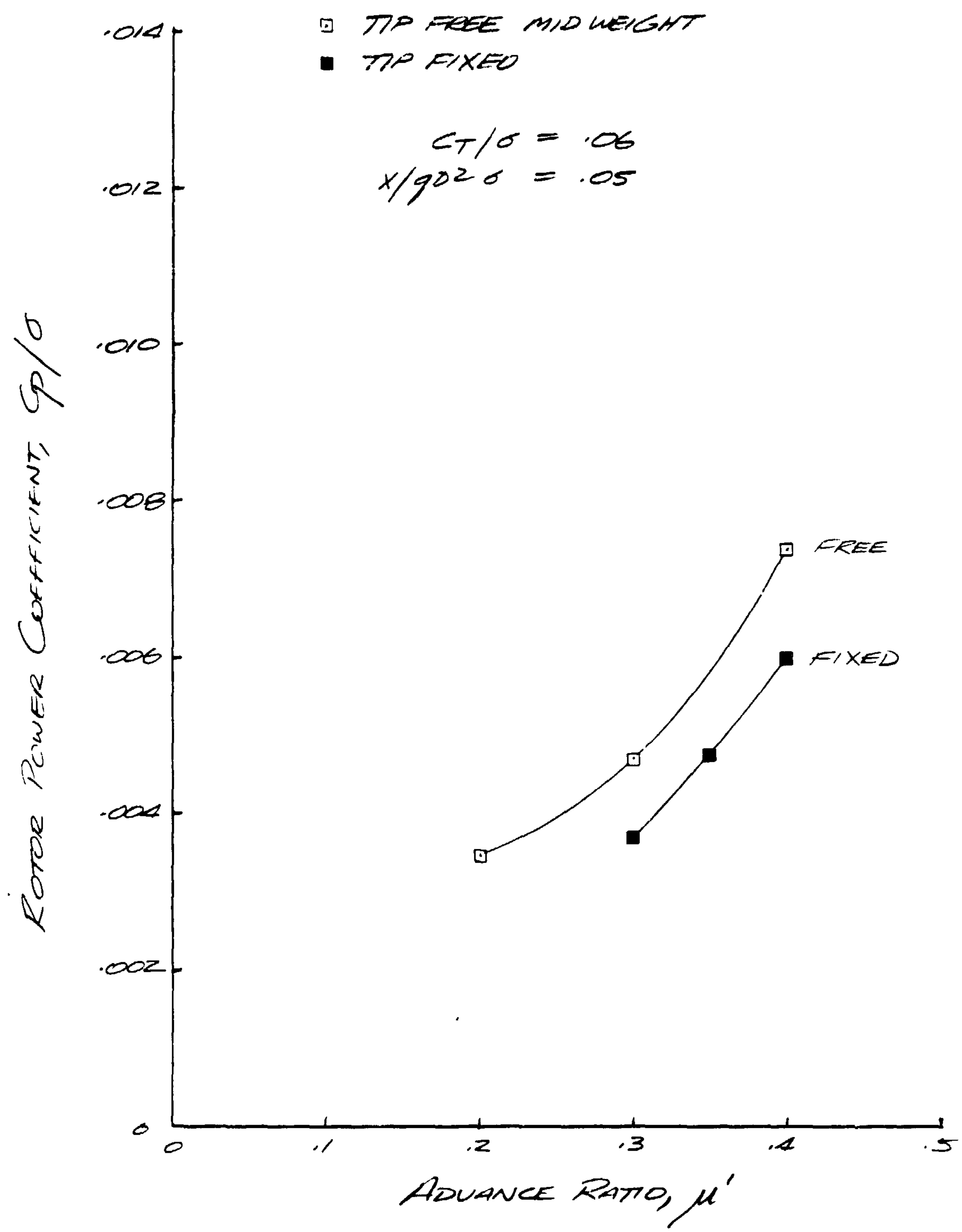
△ TIP FREE MID WEIGHT
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = .05$



KMB 10/9/81

BVWT 271 CONSTANT LIFT TIP



KMB 10/3/81

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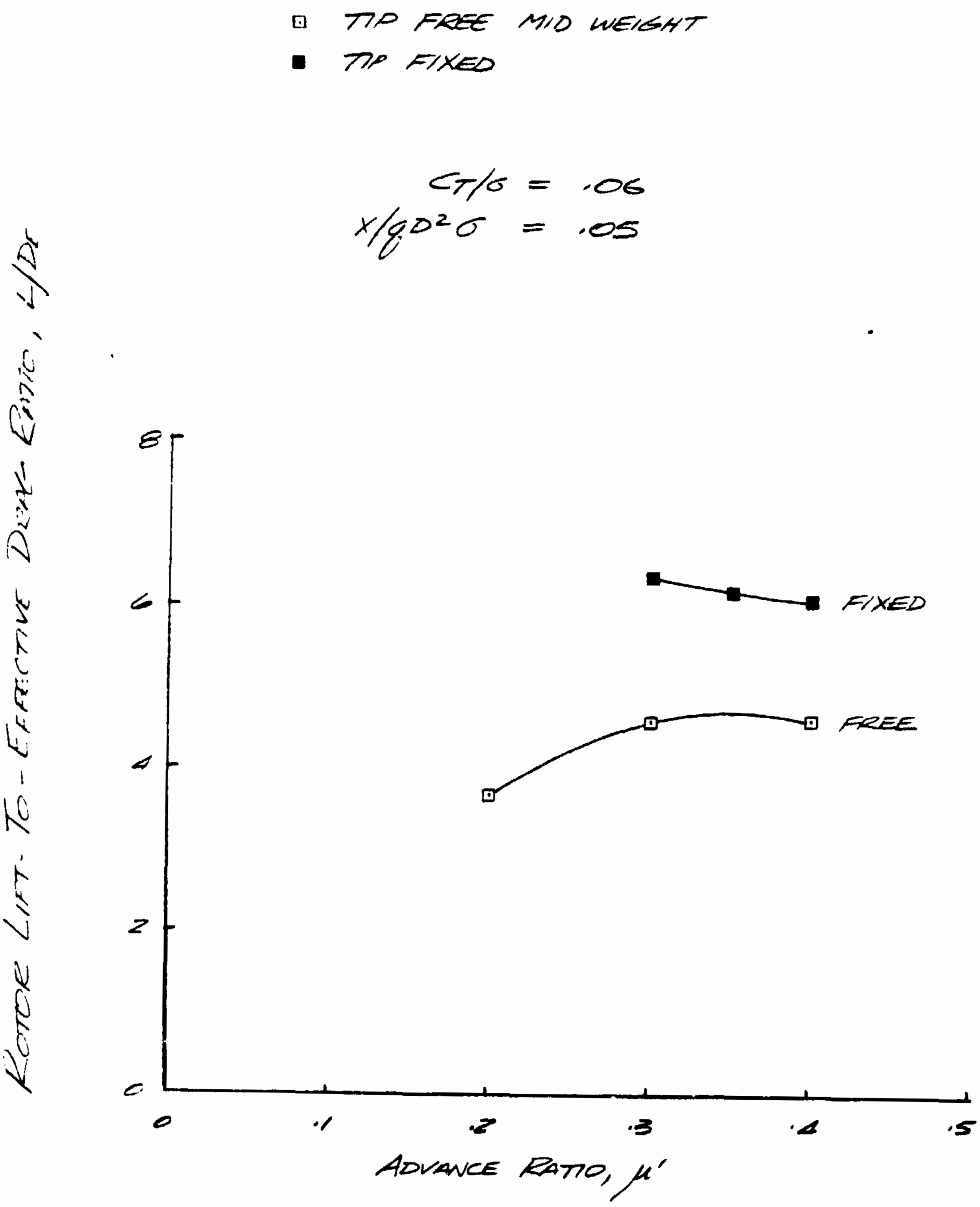
BVWT 271 CONSTANT LIFT TIP



KHO 10/9/81

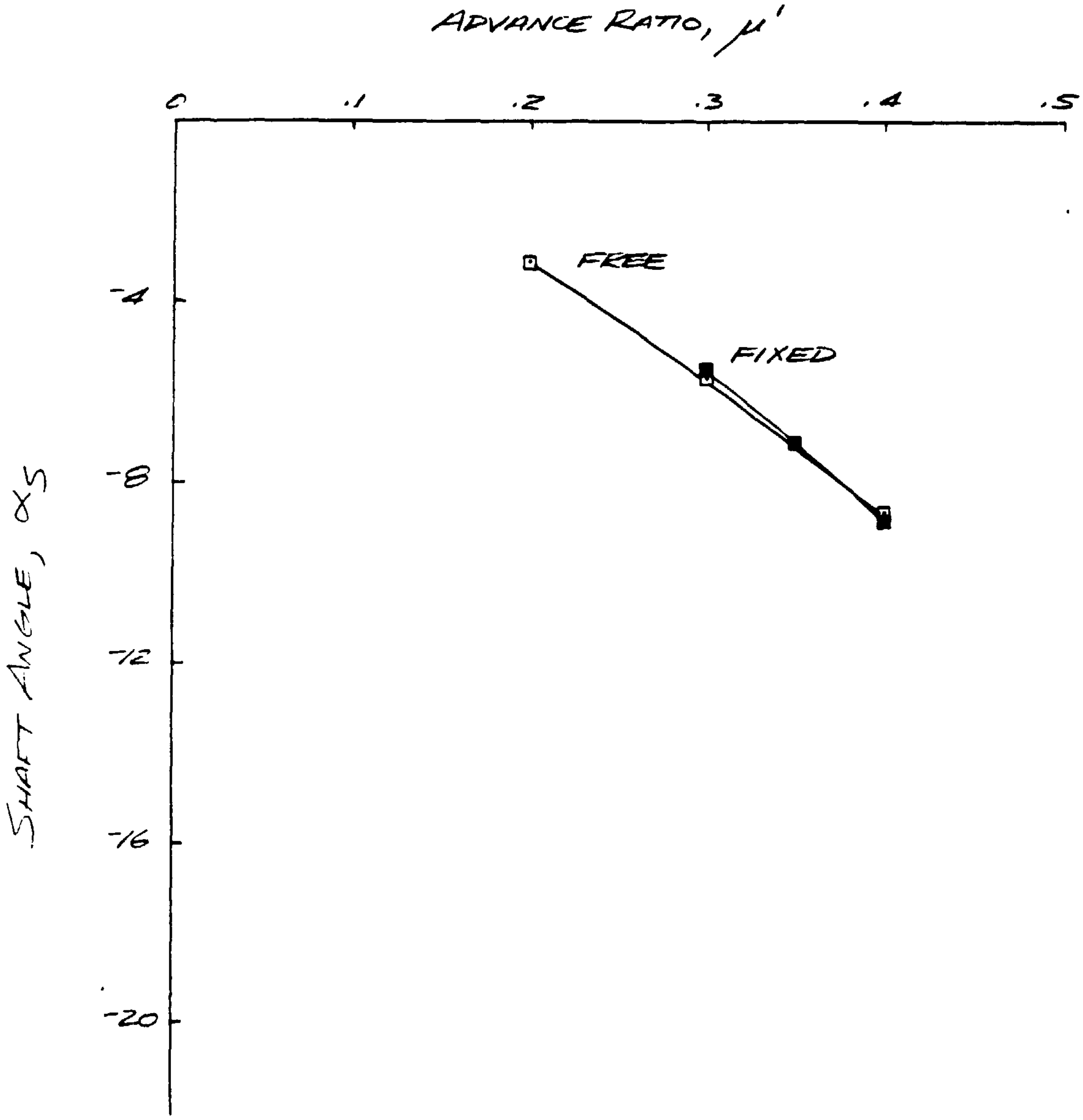
EVWT 271 CONSTANT LIFT TIP

□ TIP FREE MID WEIGHT

■ TIP FIXED

$C_T/\sigma = .06$

$X/qD^2\sigma = .05$

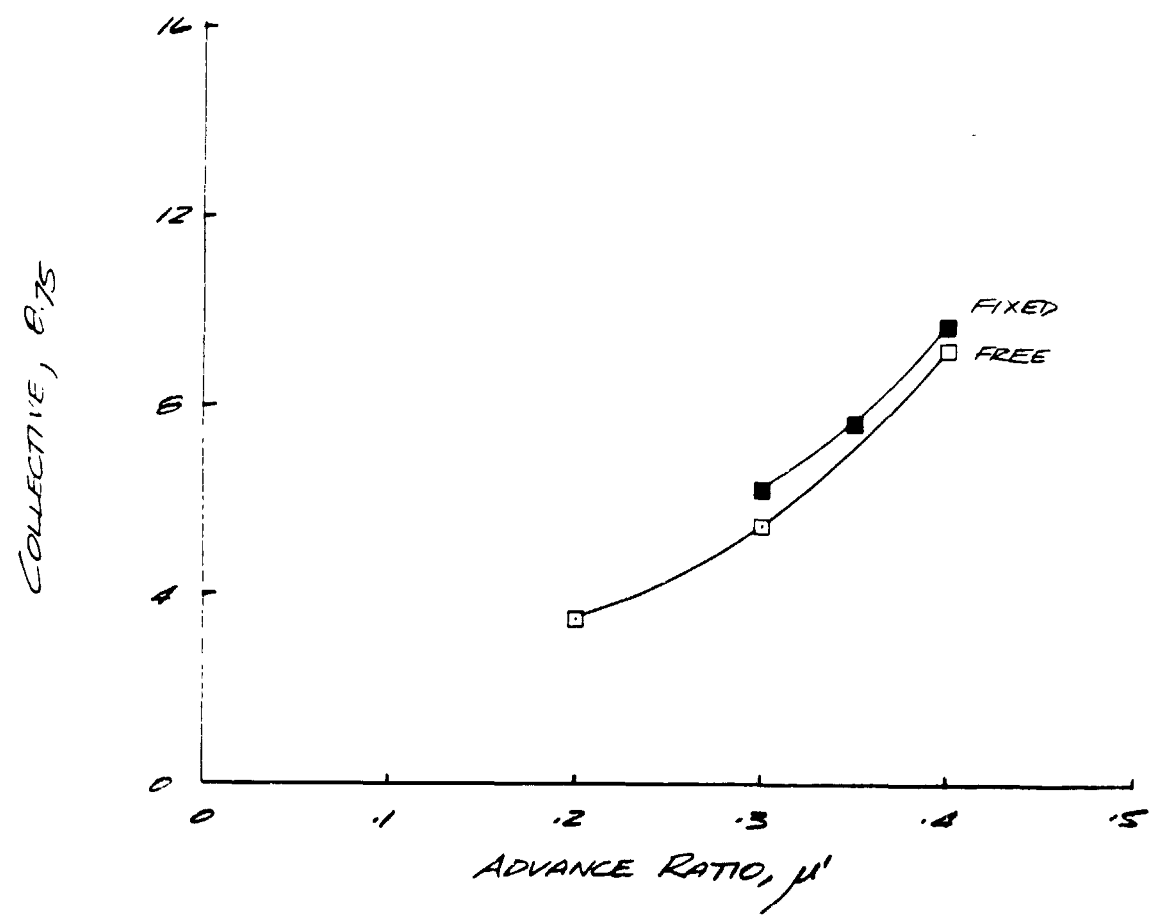


KMB 10/9/81

BVWT 271 CONSTANT LIFT TIP

□ TIP FREE MID WEIGHT
■ TIP FIXED

$C_T/\sigma = .06$
$X/qD^2\sigma = .05$



KMB 10/9/81

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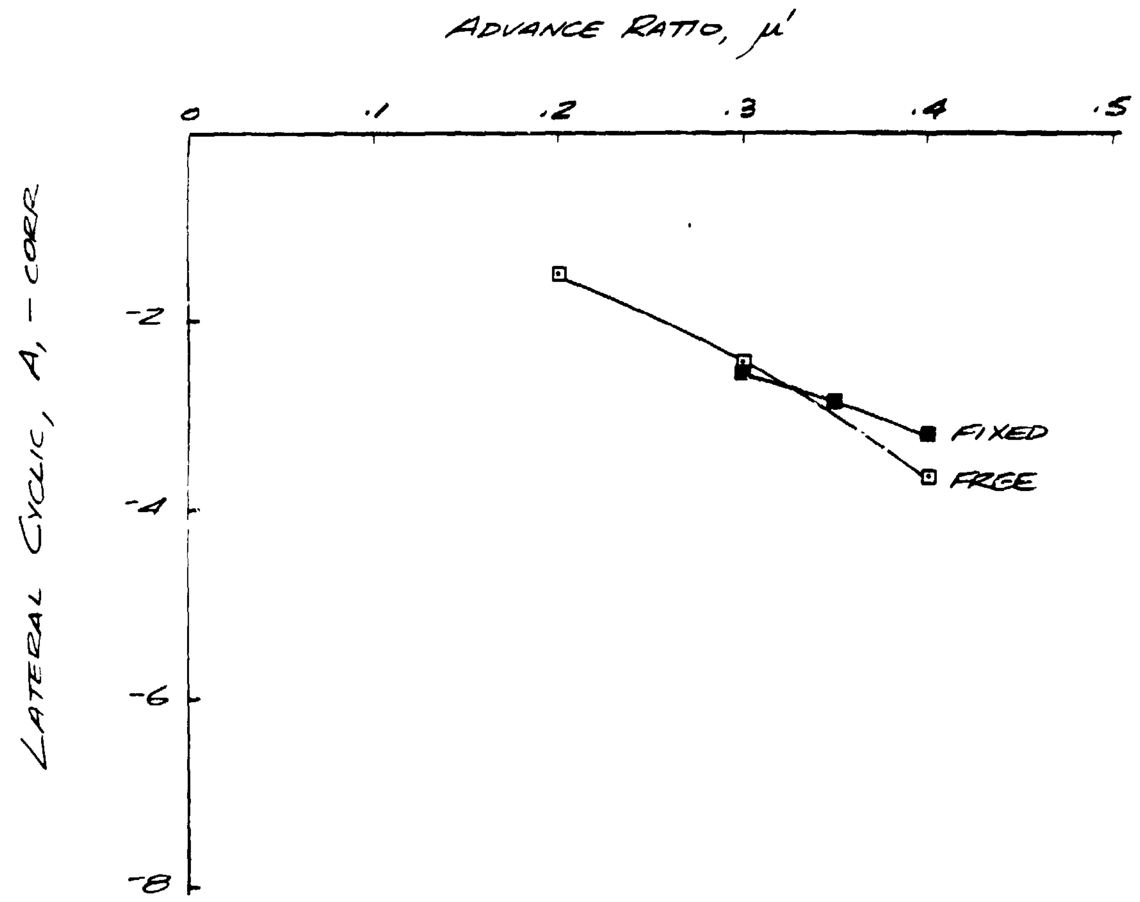
BVWT 271 CONSTANT LIFT TIP

□ TIP FREE MID WEIGHT

■ TIP FIXED

$C_T/\sigma = .06$

$X/qD^2\sigma = .05$

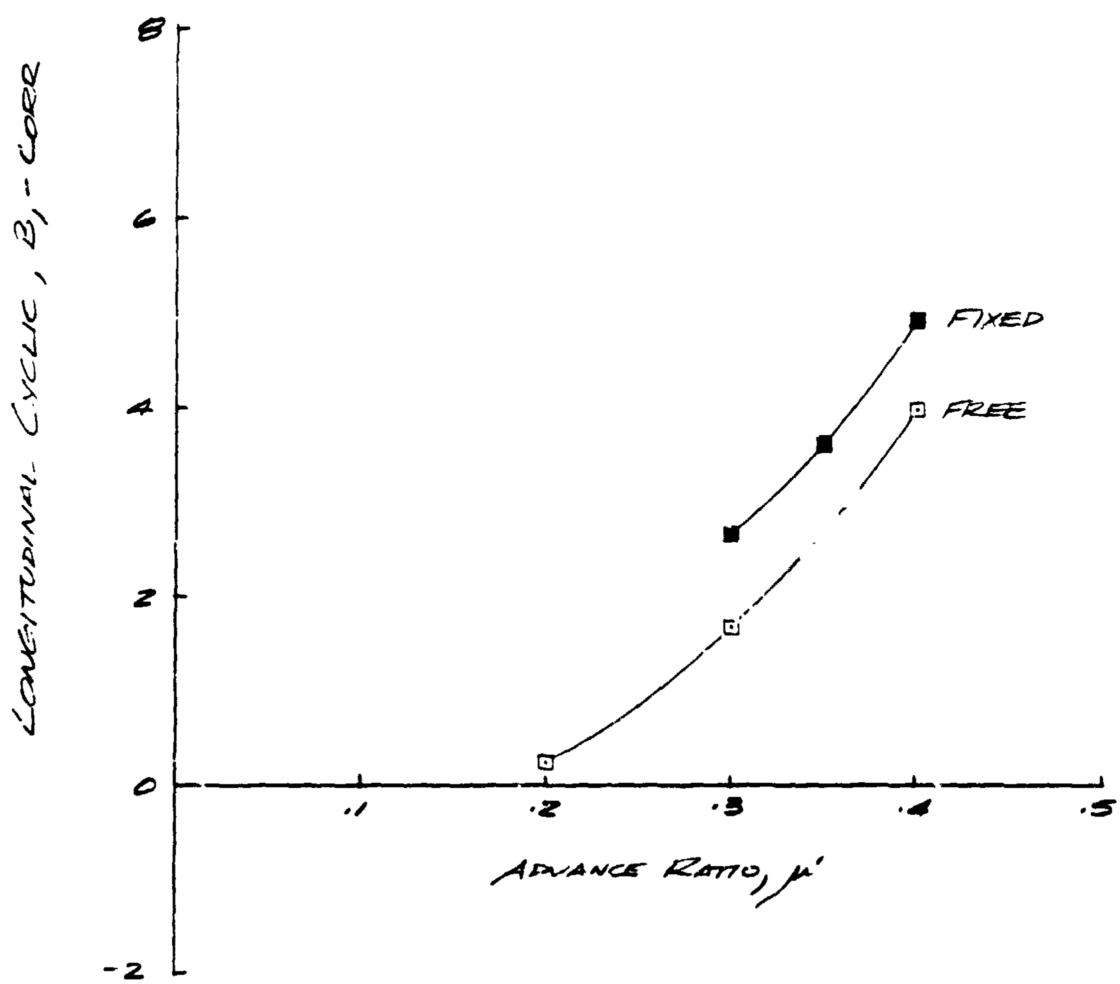


KMS 10/8/81

BVWT 271 CONSTANT LIFT TIP

⊡ TIP FREE MIDWEIGHT
■ TIP FIXED

$C_T/\sigma = .06$
$X/qD^2\sigma = .05$

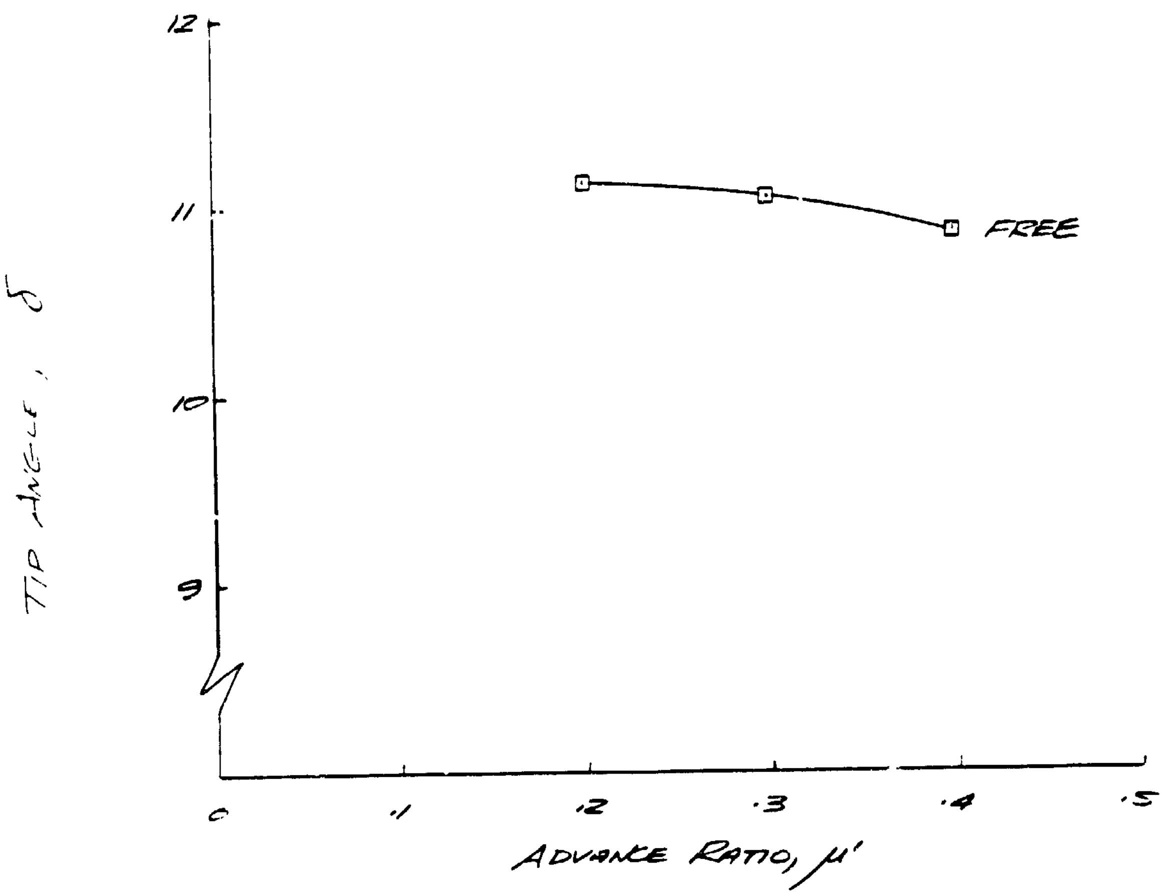


KMIC 10/6/81

BVWT 271 CONSTANT LIFT TIP

TIP FREE MID WEIGHT
(TIP FIXED $\delta = 0$)

$C_T/\sigma = .06$
$\ldots^2\sigma = .05$



KMB 10/?/81

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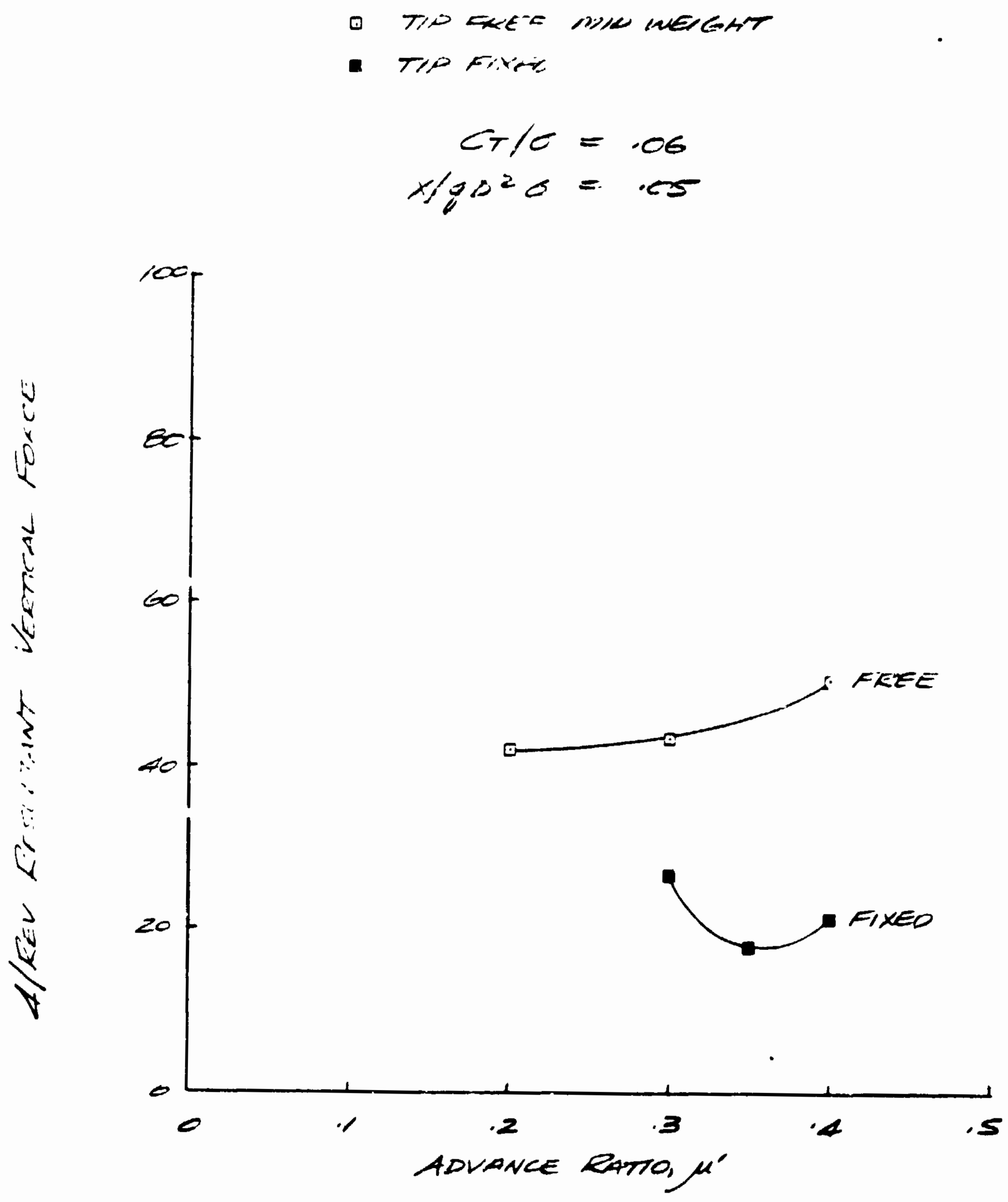

KMB 11/9/81

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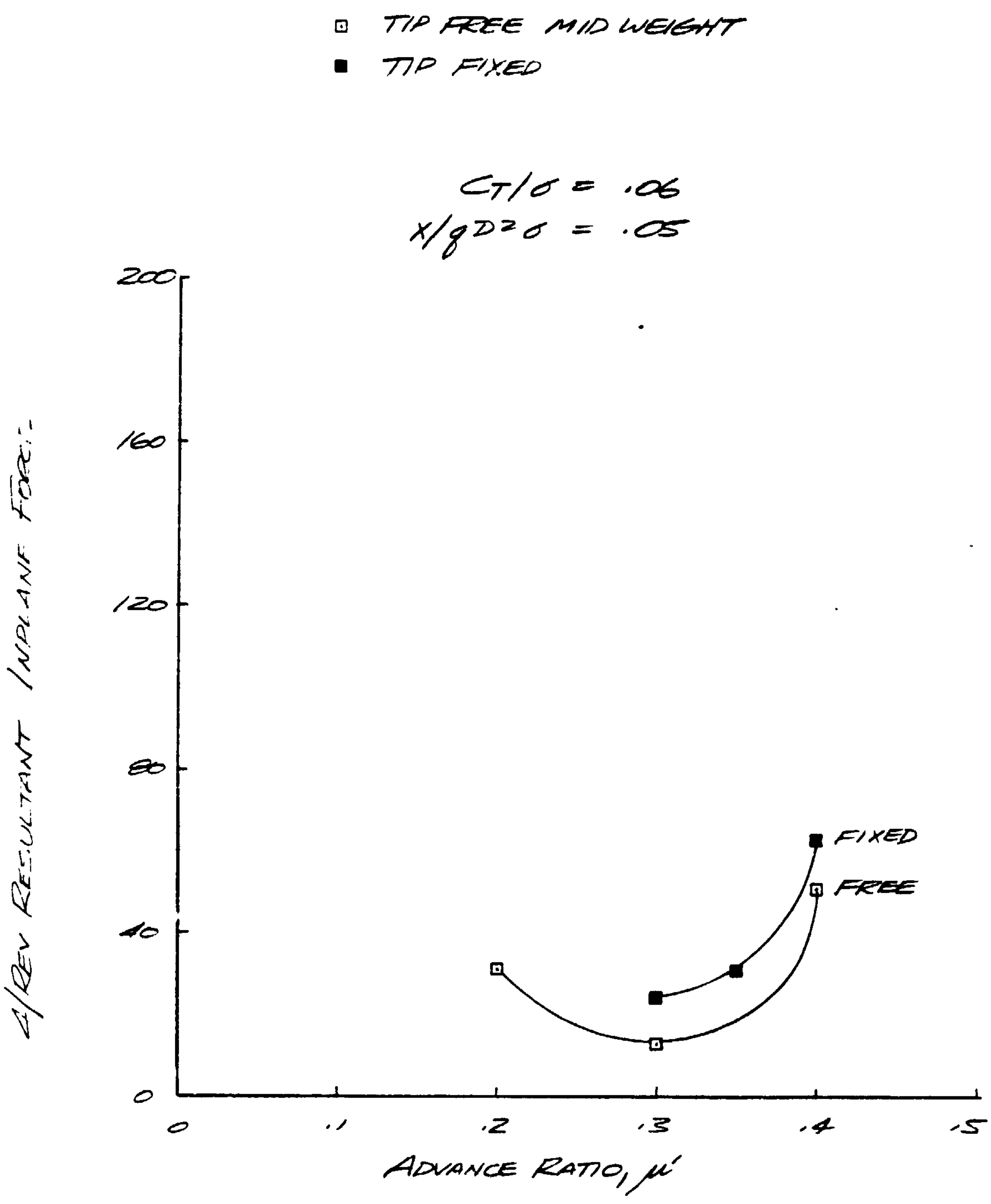
BVWT 271 CONSTANT LIFT TIP



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KING 10/9/81

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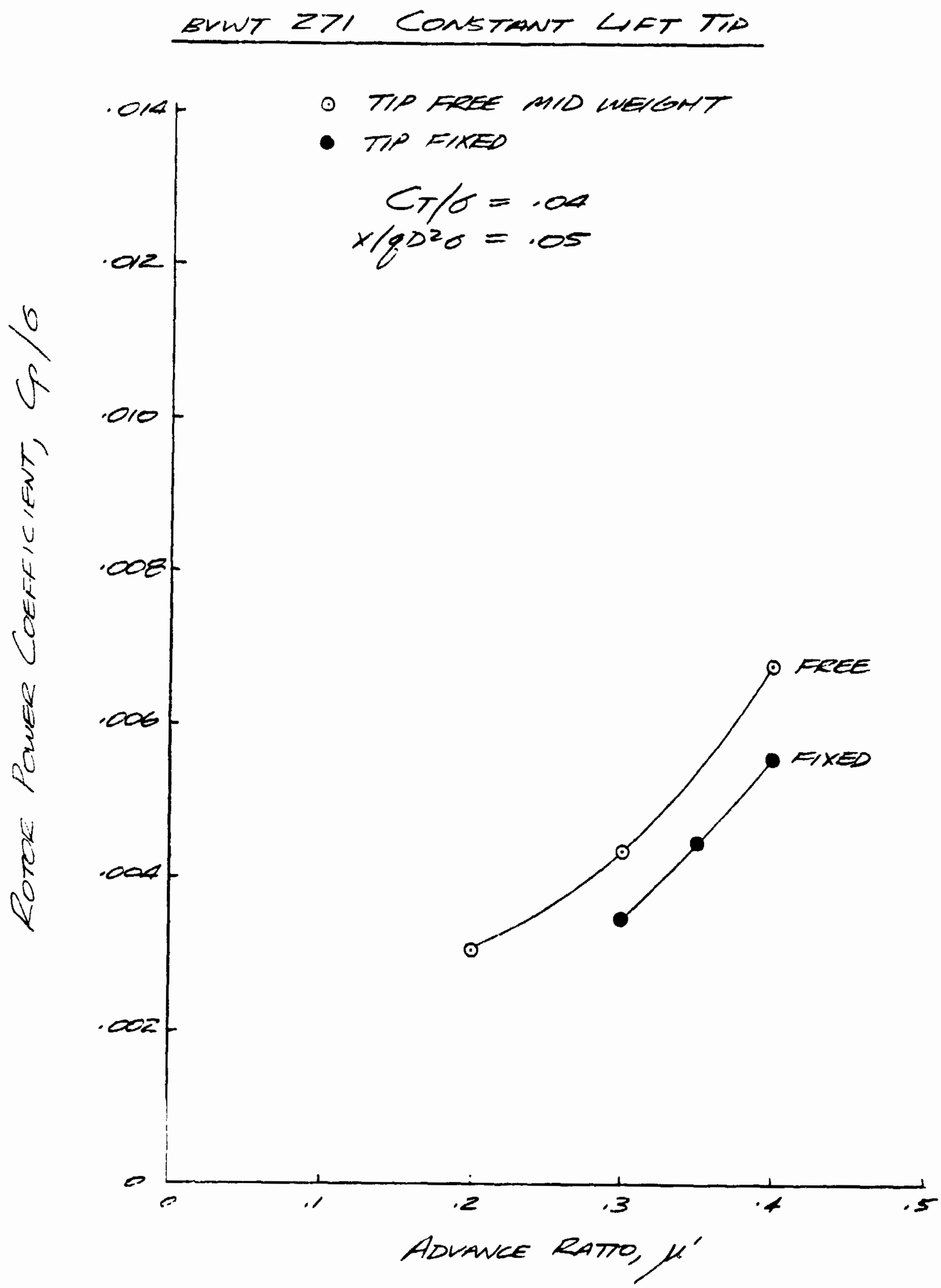

KMB 10/9/81

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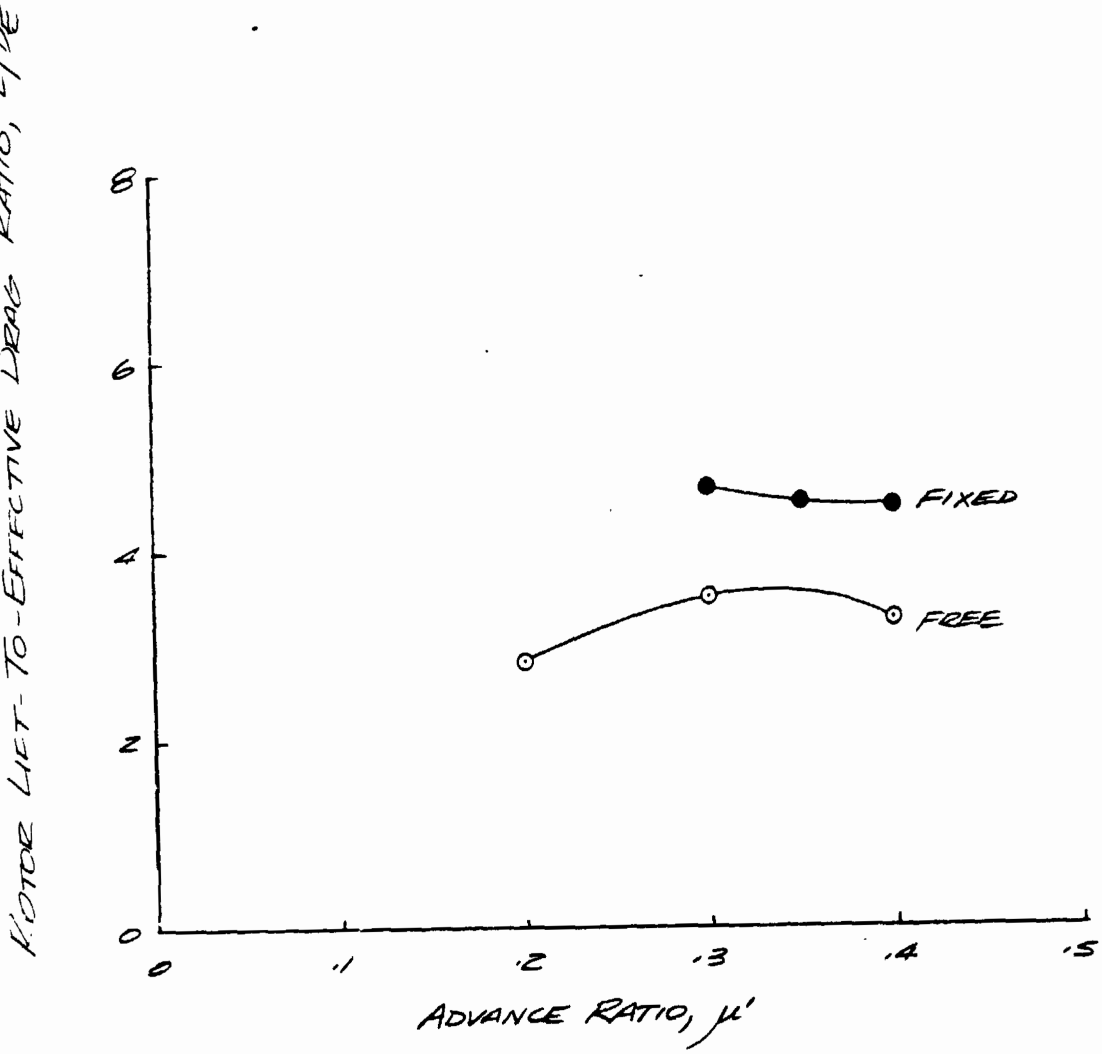
EVWT 271 CONSTANT LIFT TIP

○ TIP FREE MID WEIGHT
● TIP FIXED

$C_T/\sigma = .04$
$X/qD^2\sigma = .05$



KMB 10/9/81

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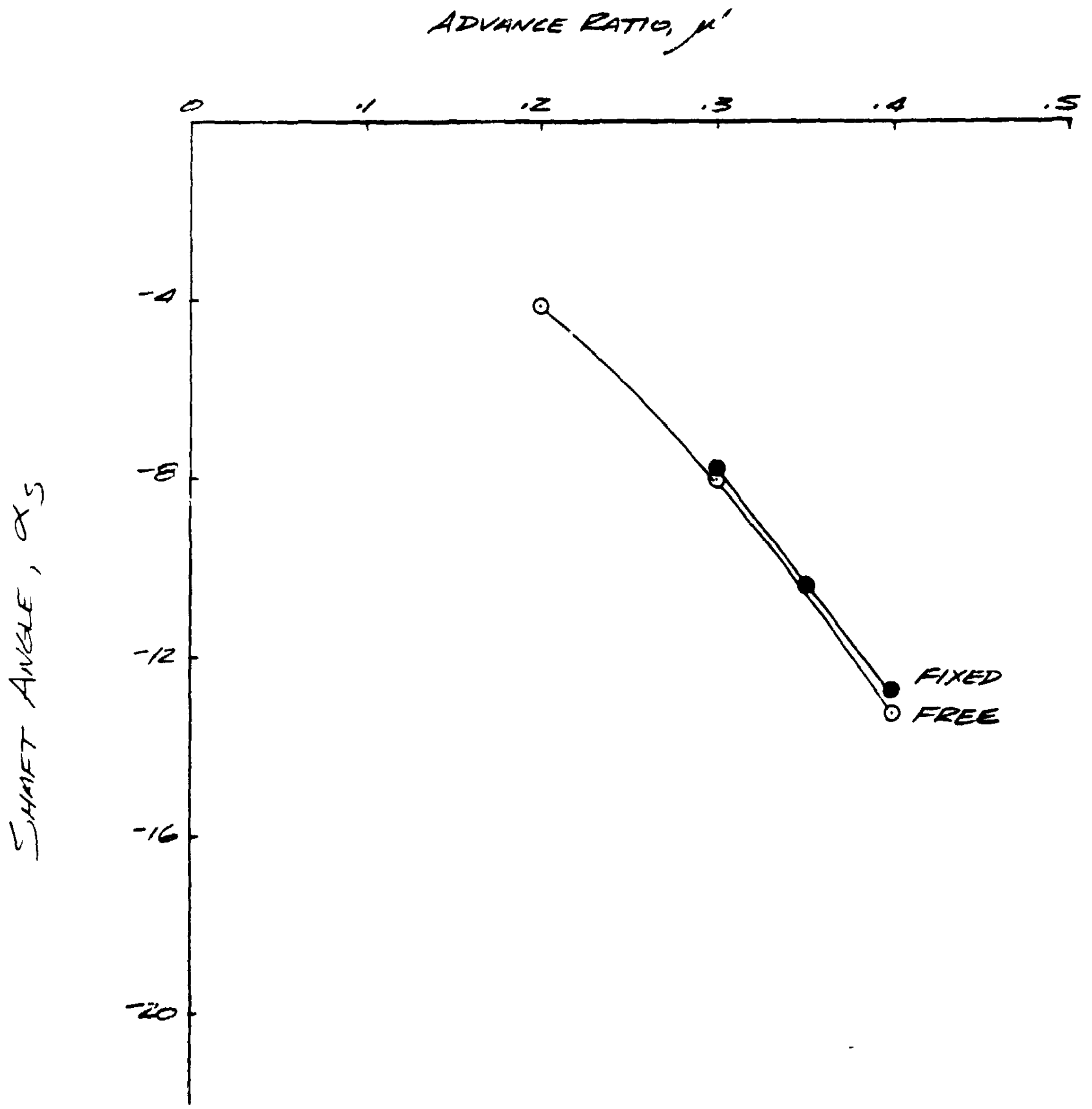
BVWT 271 CONSTANT LIFT TIP

⊙ TIP FREE MID WEIGHT

● TIP FIXED

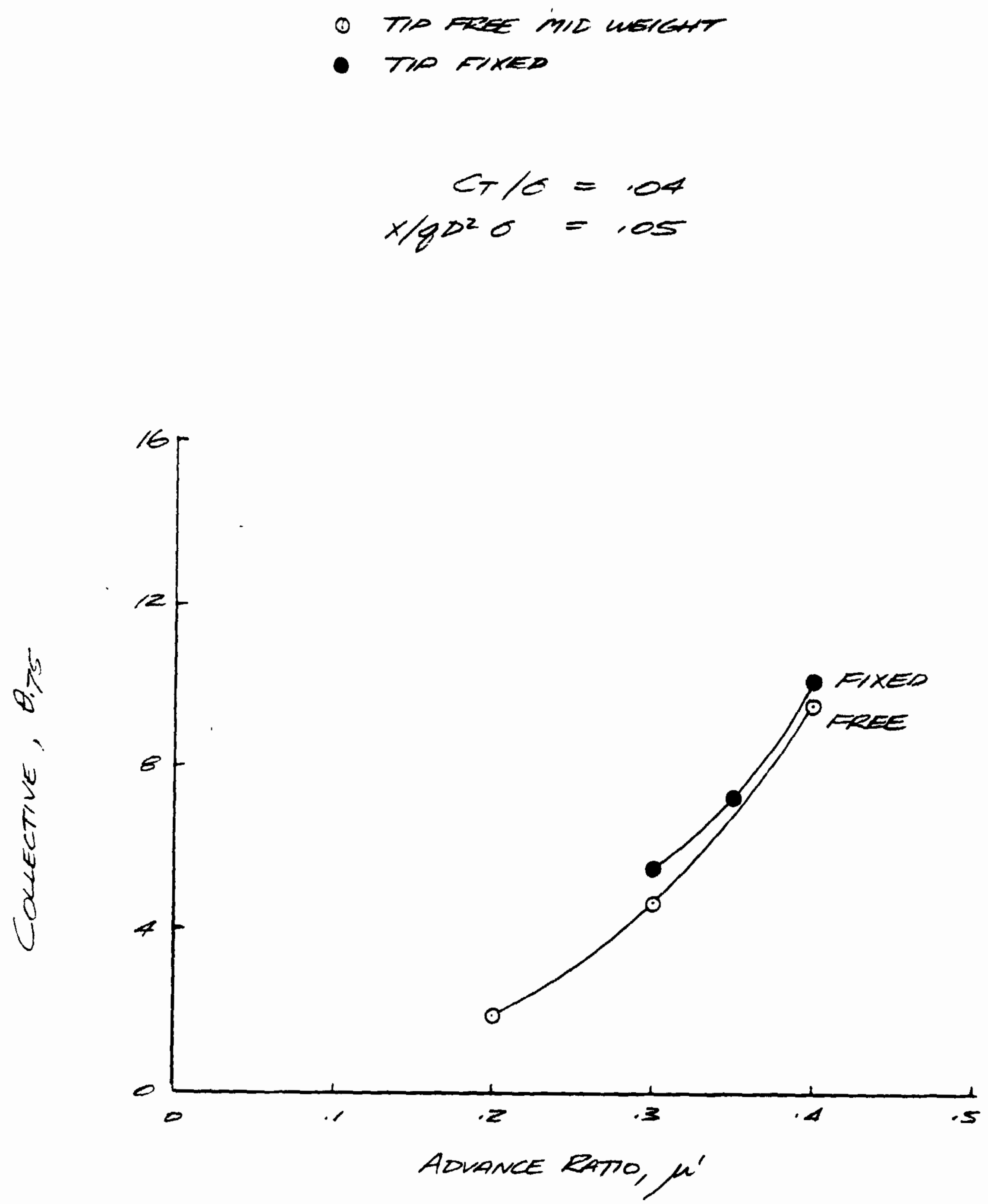
$C_T/\sigma = .04$

$X/qD^2\sigma = .05$



KMB 10/9/81

BVWT 271 CONSTANT LIFT TIP



KMB 10/9/81

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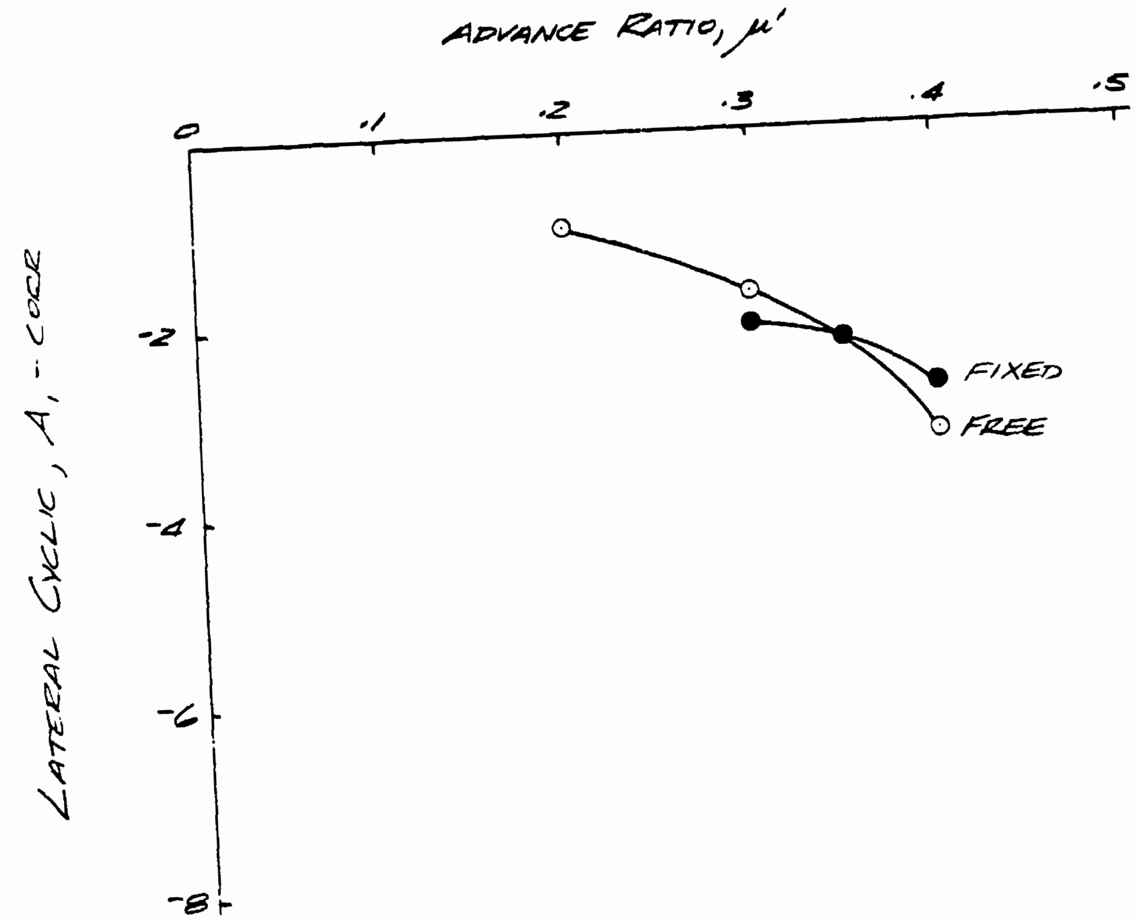
BVWT 271 CONSTANT LIFT TIP

⊙ TIP FREE MID WEIGHT

● TIP FIXED

$C_T/\sigma = .04$

$X/qD^2\sigma = .05$

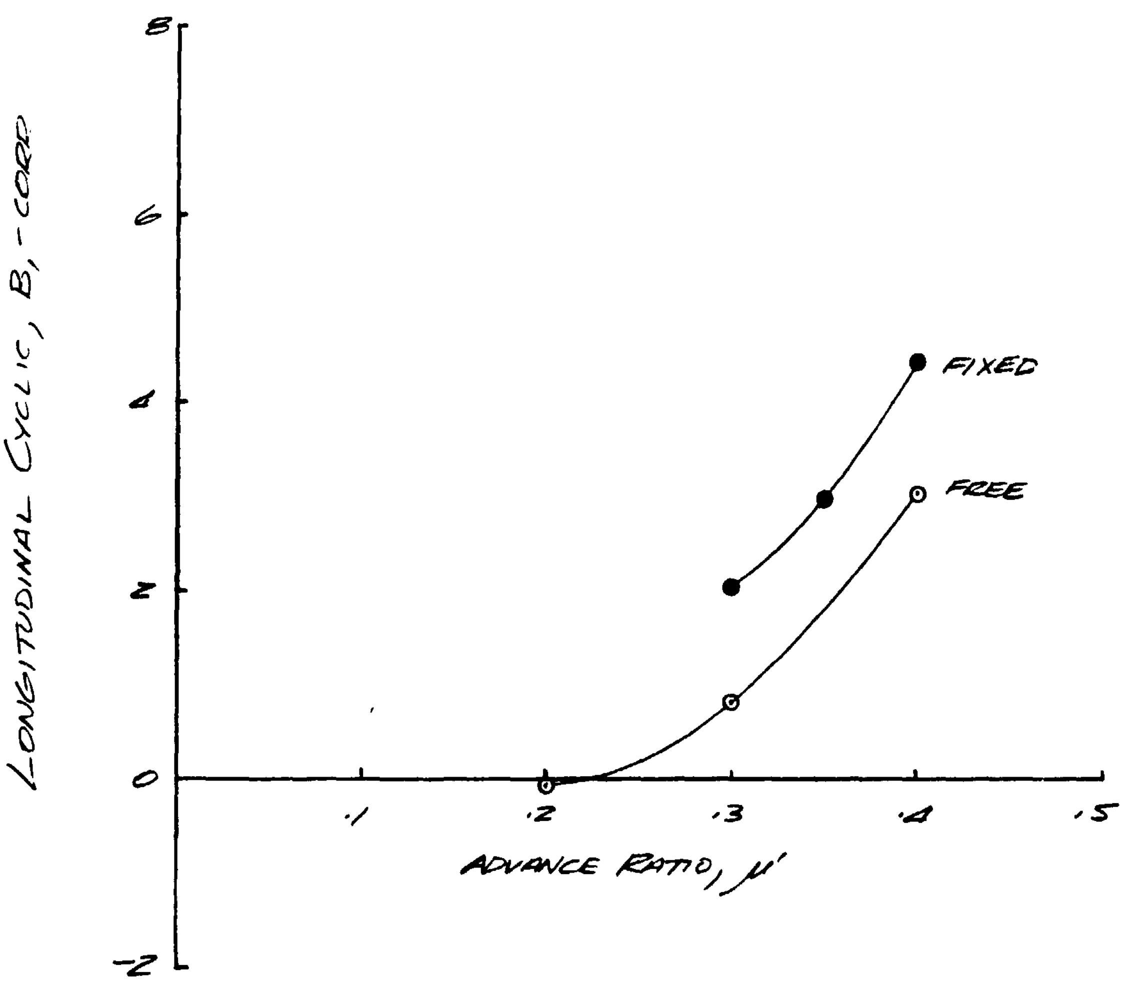


KPPG 10/9/81

BVWT 271 CONSTANT LIFT TIP

○ TIP FREE MID WEIGHT
● TIP FIXED

$$C_T/\sigma = .04$$
$$X/qD^2\sigma = .05$$

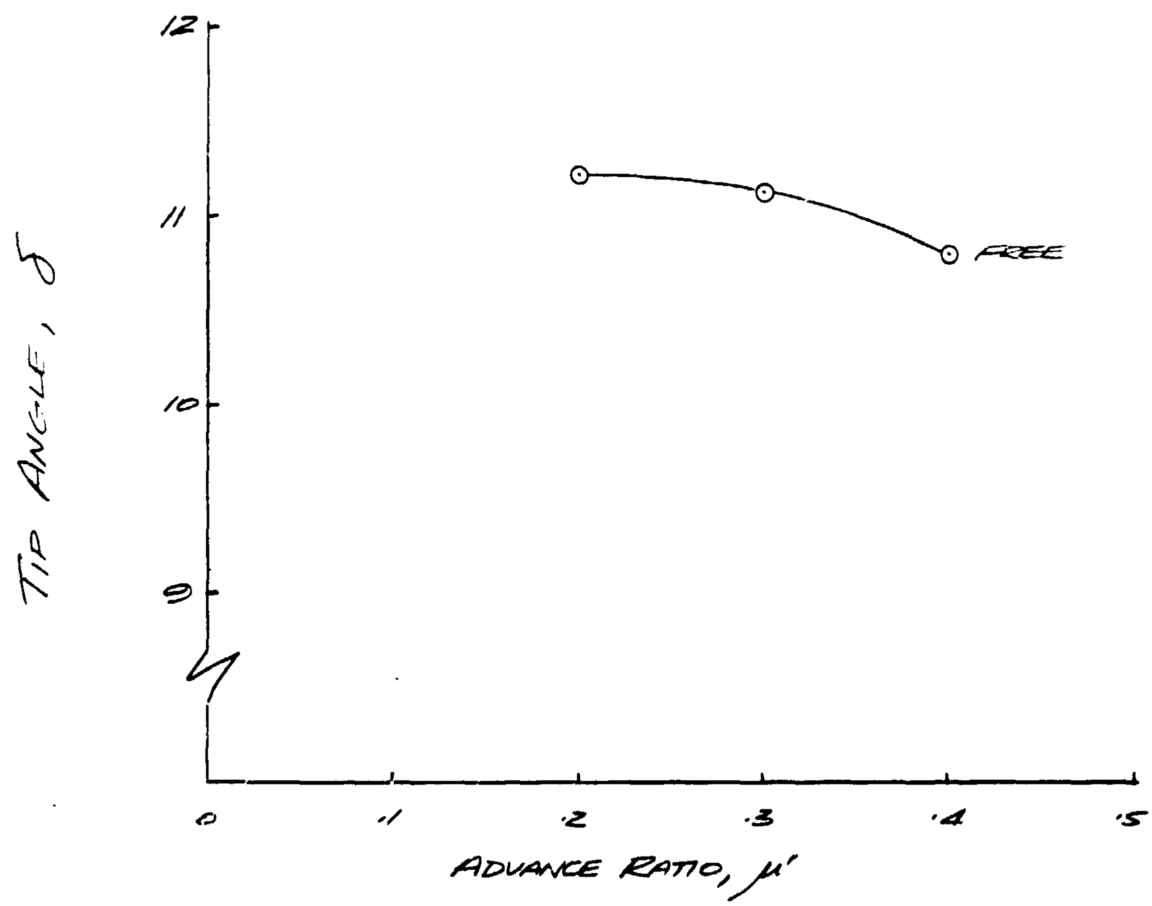


KMC 10/8/81

BVWT 271 CONSTANT LIFT TIP

⊙ TIP FREE MID WEIGHT
(TIP FIXED $\delta = 0$)

$C_T/\sigma = .04$
$X/qD^2\sigma = .05$

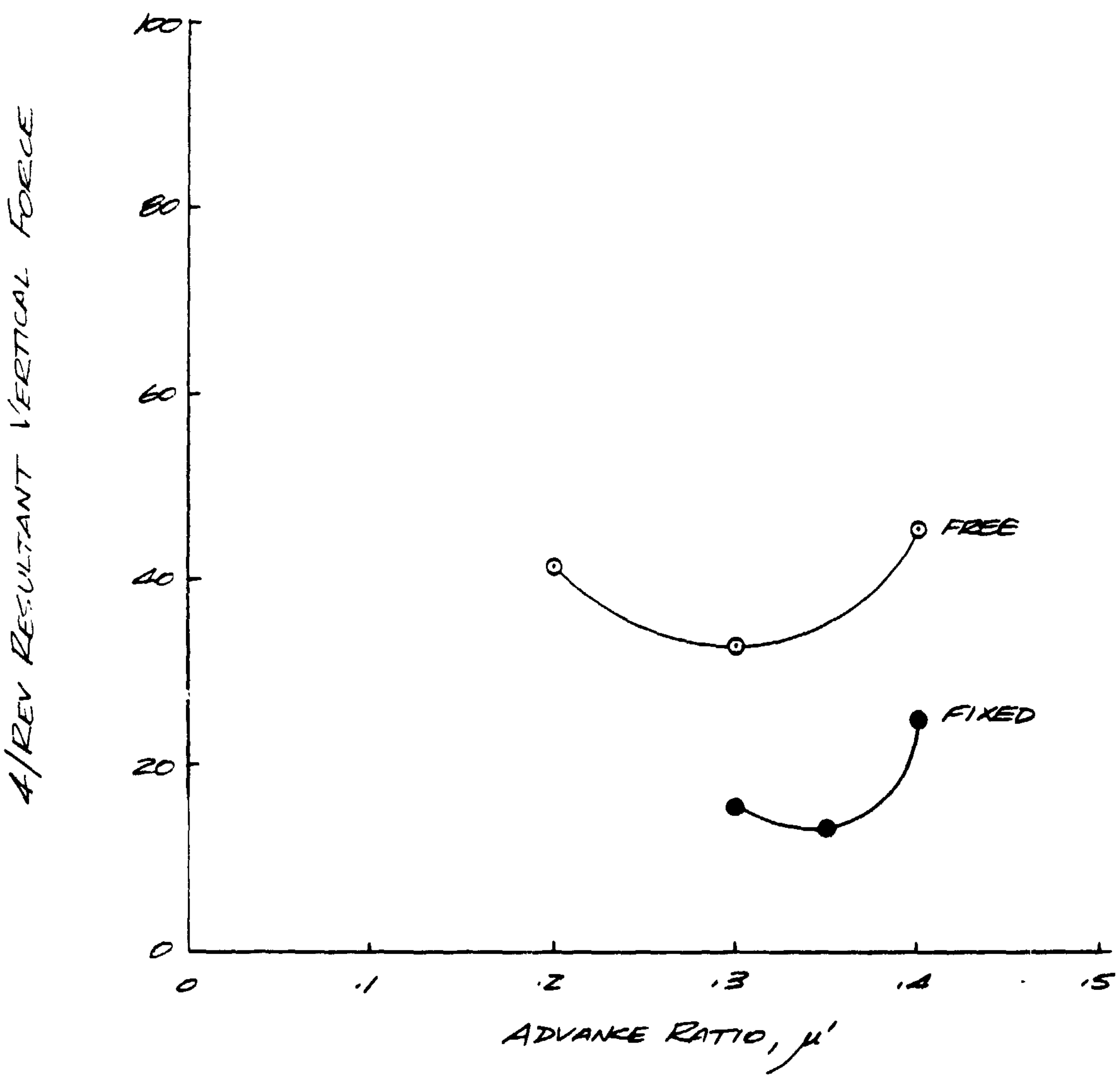


KMB 10/9/81

BVWT 271 CONSTANT LIFT TIP

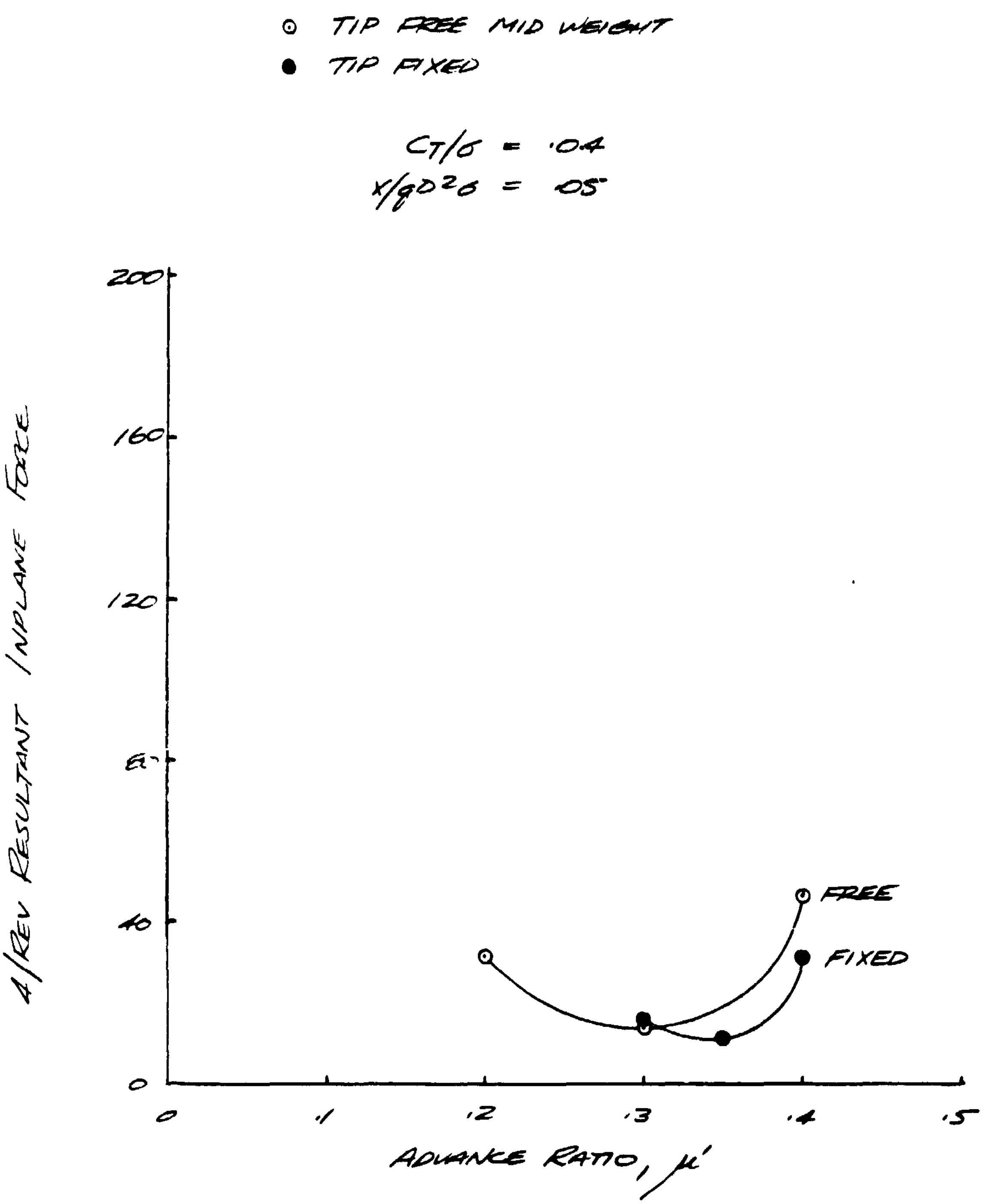
⊙ TIP FREE MID WEIGHT
● TIP FIXED

$C_T/\sigma = .04$
$X/qD^2\sigma = .05$



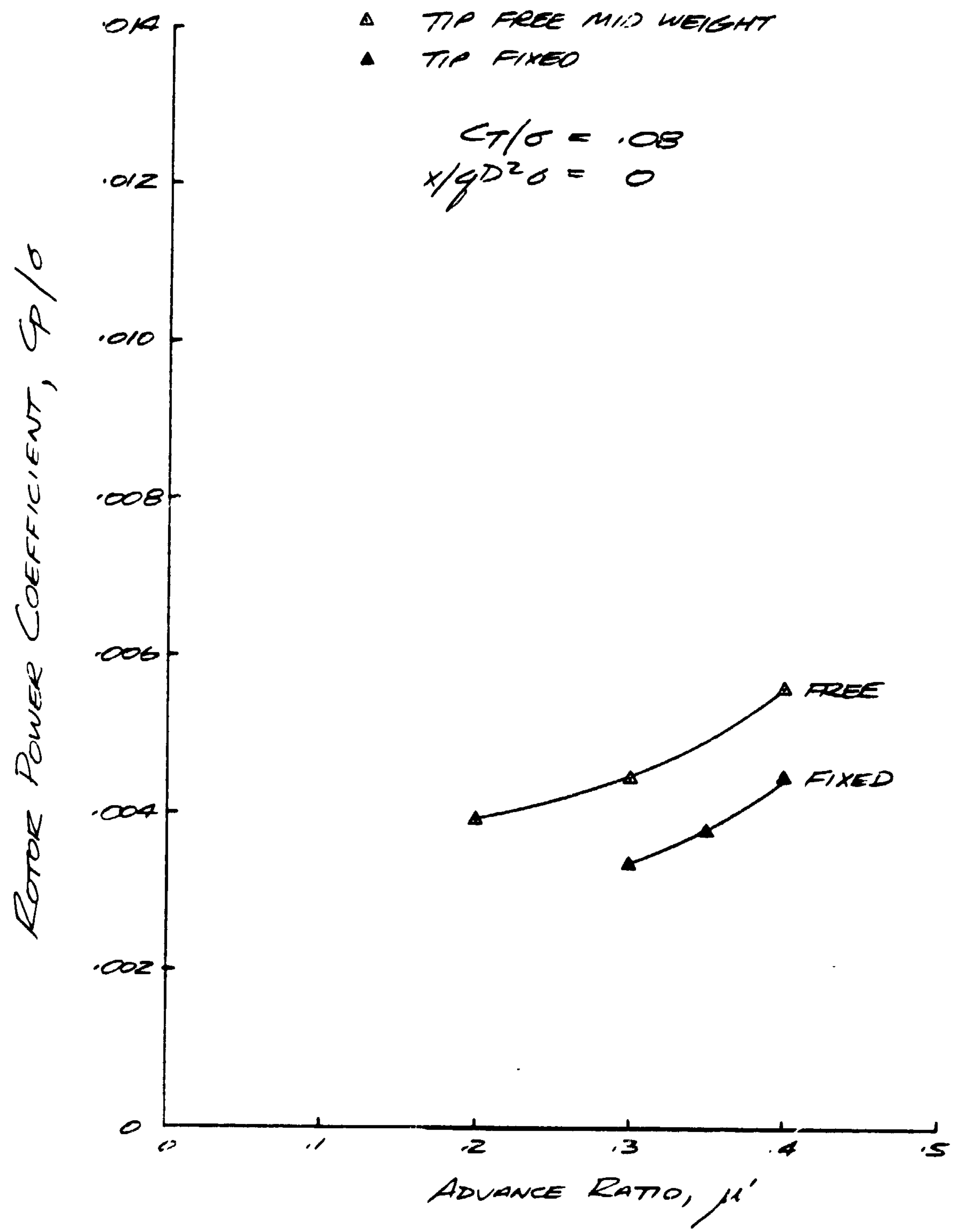
KMB 10/3/81

BVWT 271 CONSTANT LIFT TIP



KMB 10/9/81

BVWT 271 CONSTANT LIFT TIP



KMB 10/8/81

BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
▲ TIP FIXED

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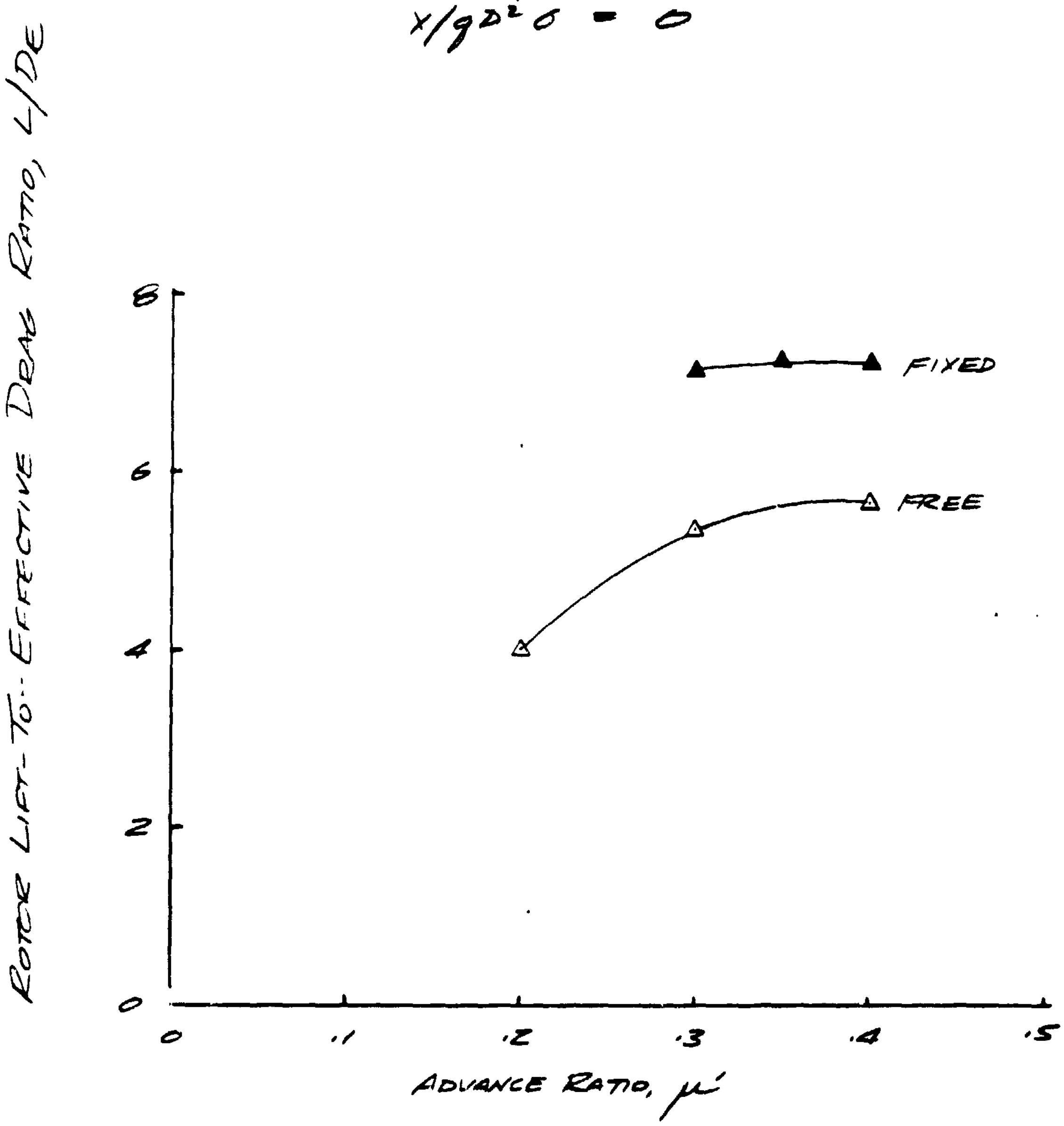
$X/qD^2\sigma = 0$



KMB 10/8/81

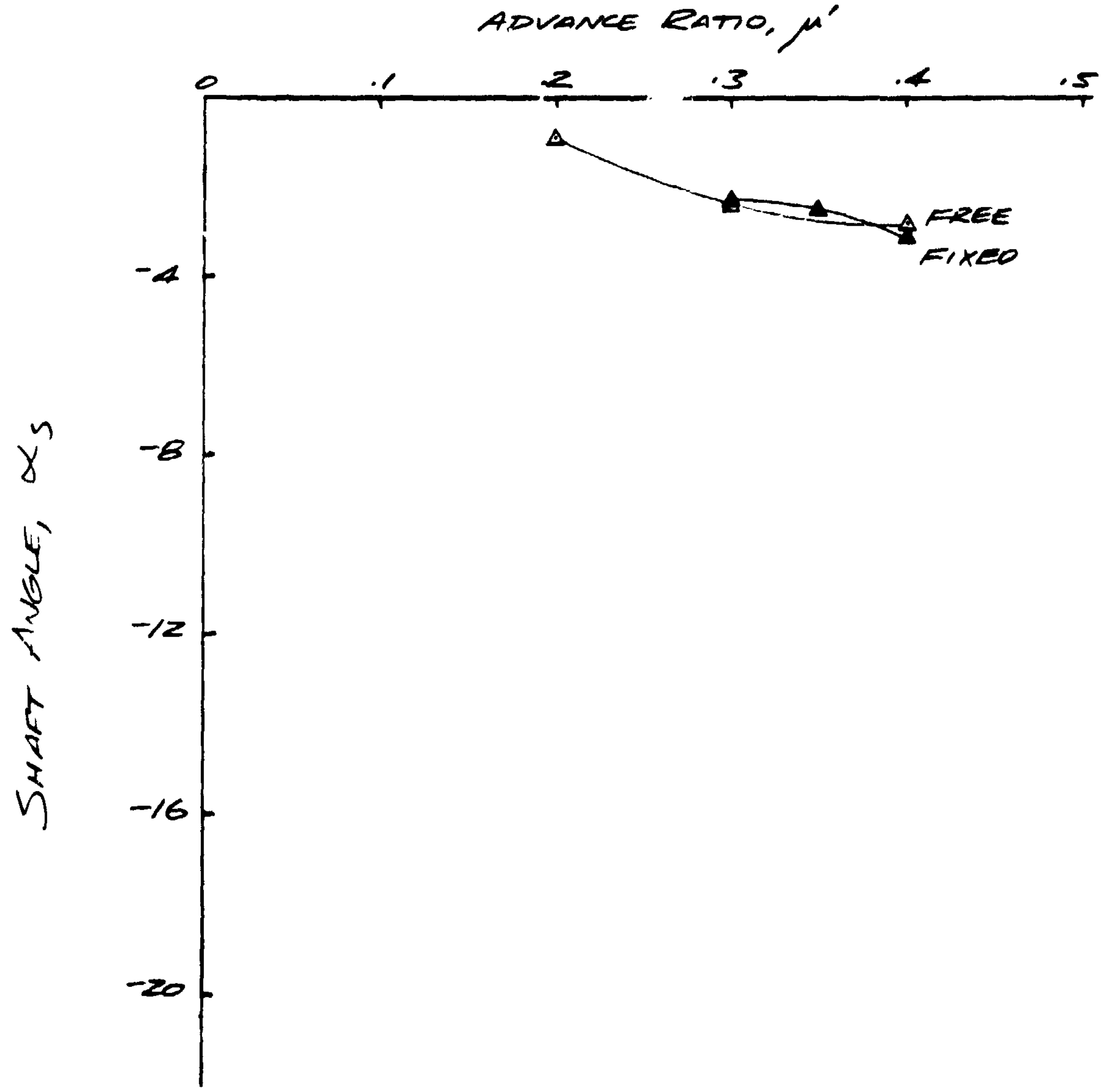
BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT

▲ TIP FIXED

$C_T/\sigma = .08$

$X/qD^2\sigma = 0$

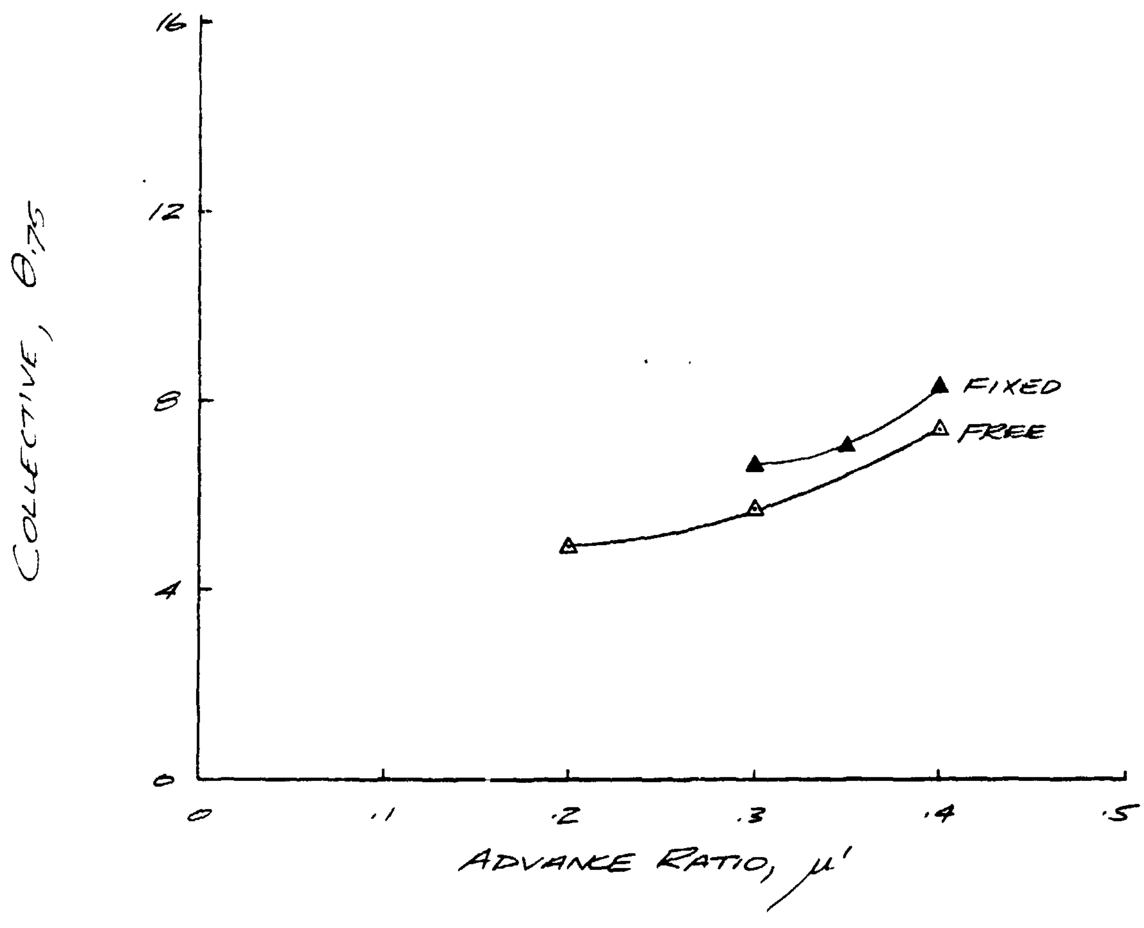


KMK 10/8/81

BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = 0$

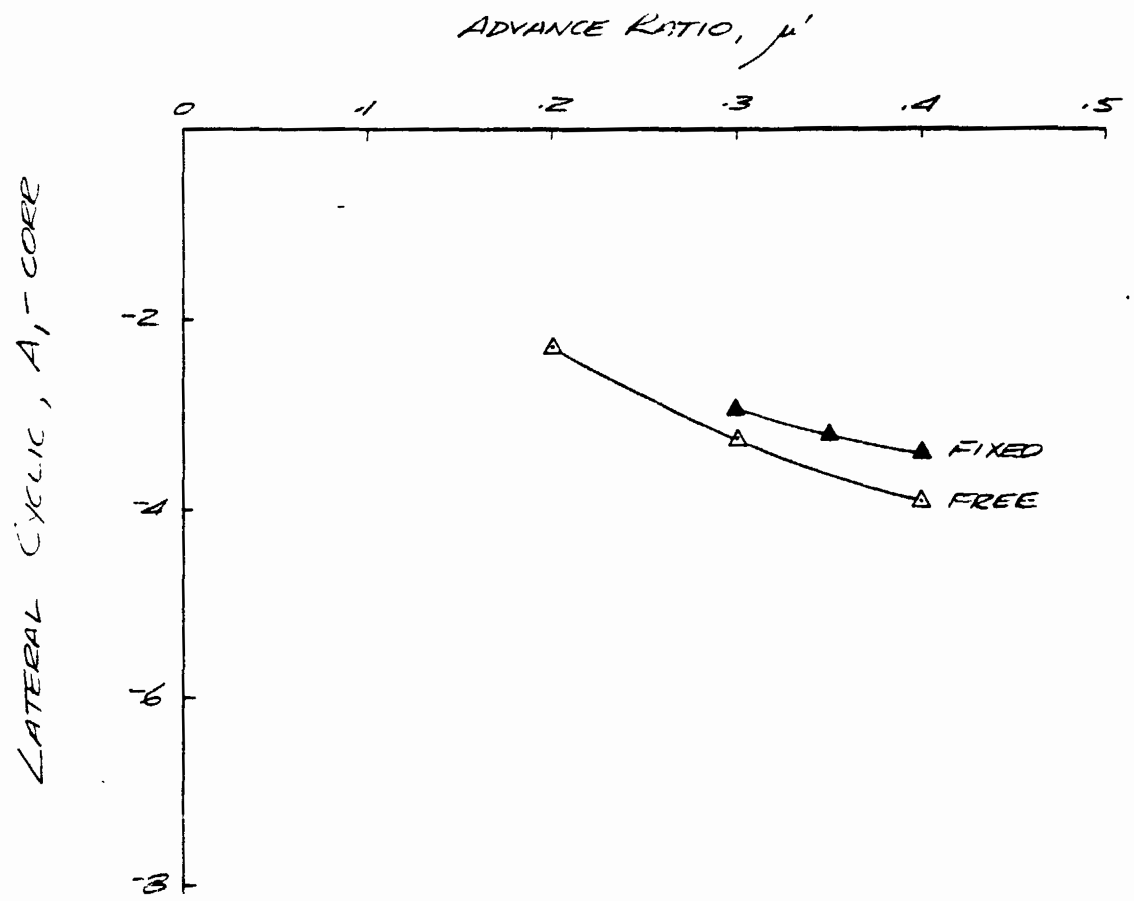


KMB 10/5/81

BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = 0$



KMB 10/8/81

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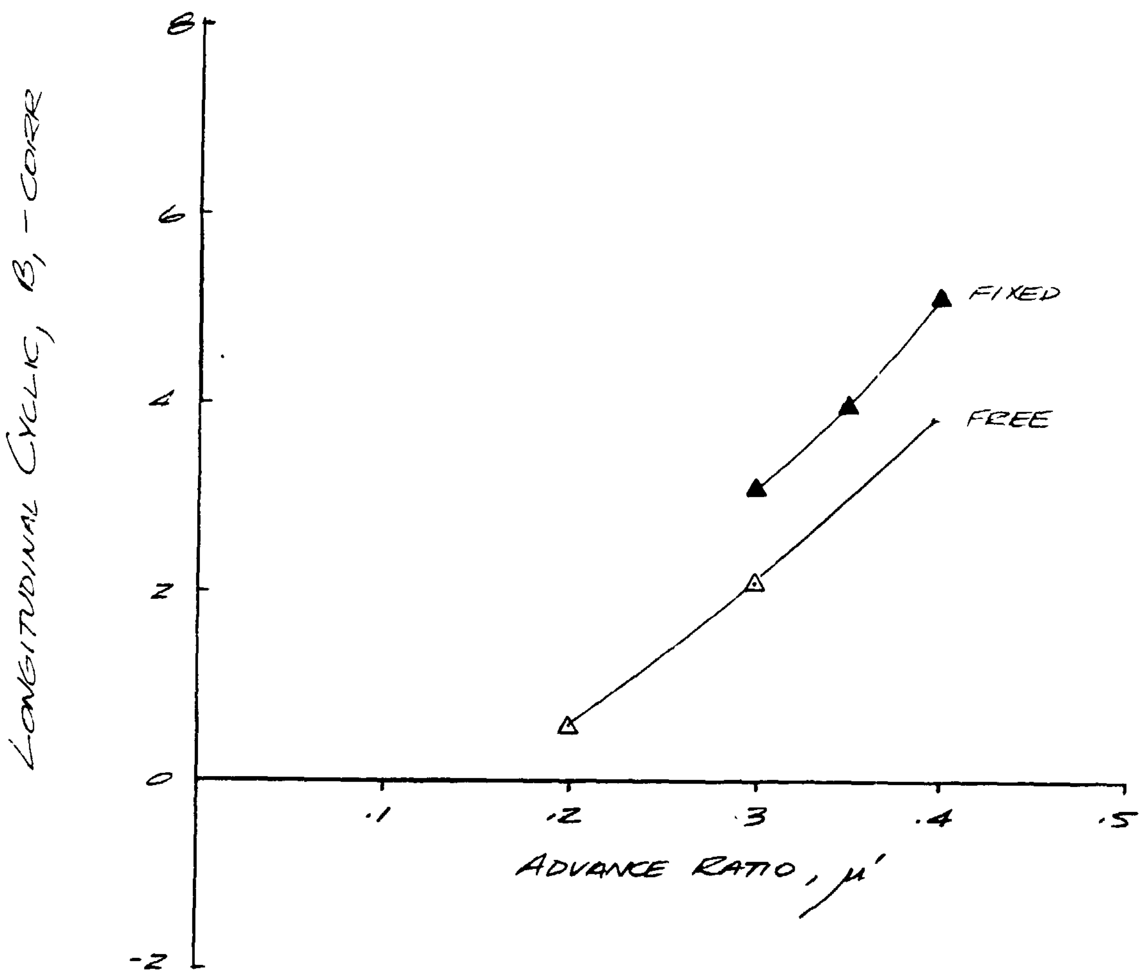
EVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = 0$



KMB 10/8/81

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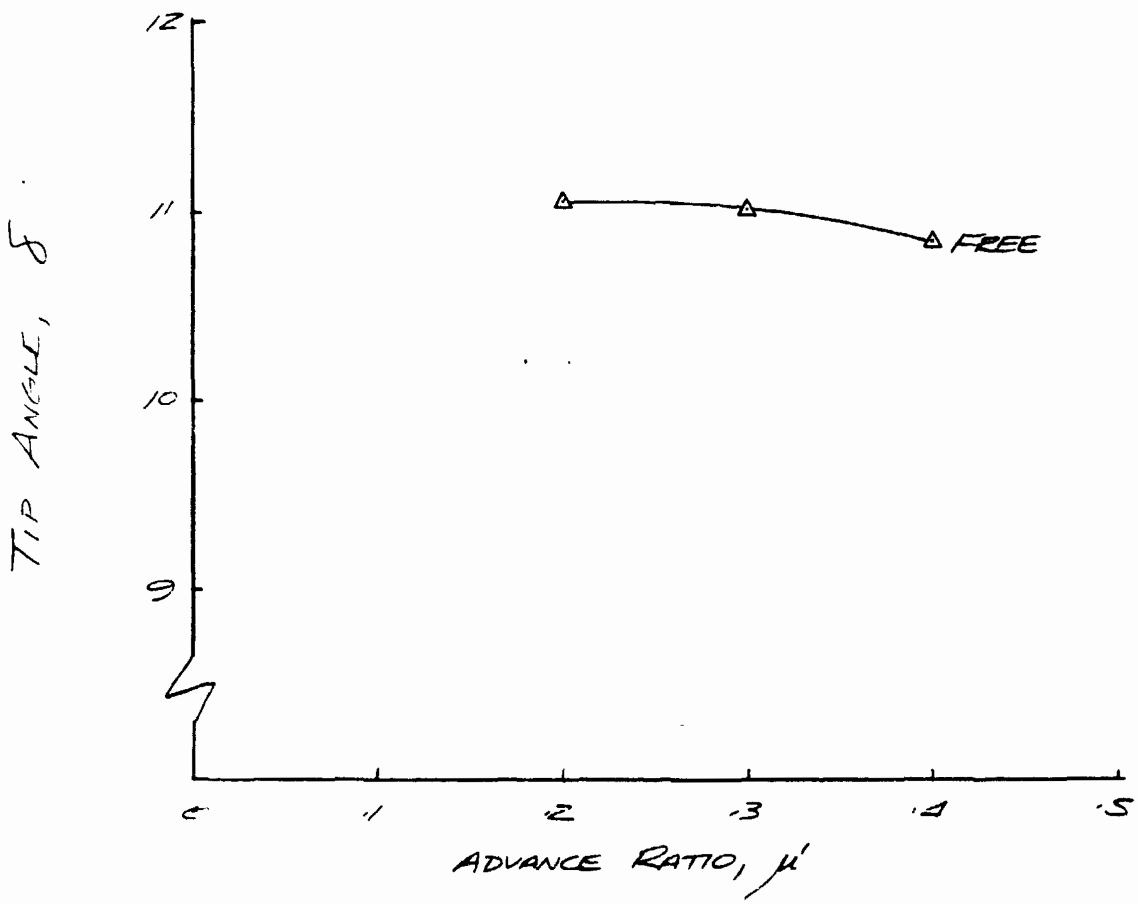
EVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
(TIP FIXED $\delta = 0$)

$C_T/\sigma = .08$
$X/qD^2\sigma = 0$



KMB 10/8/81

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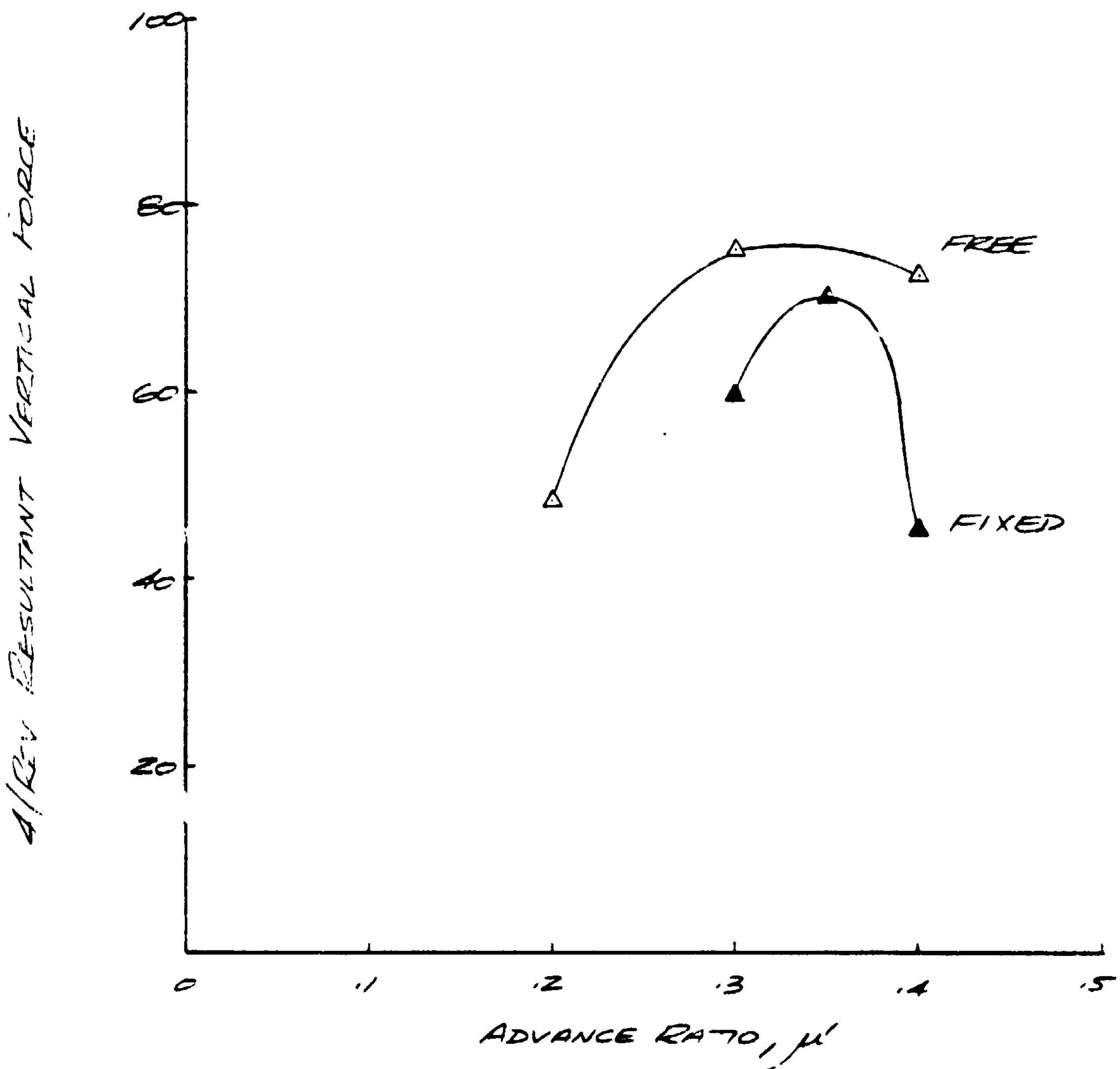
BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = 0$



KMS 10/8/81

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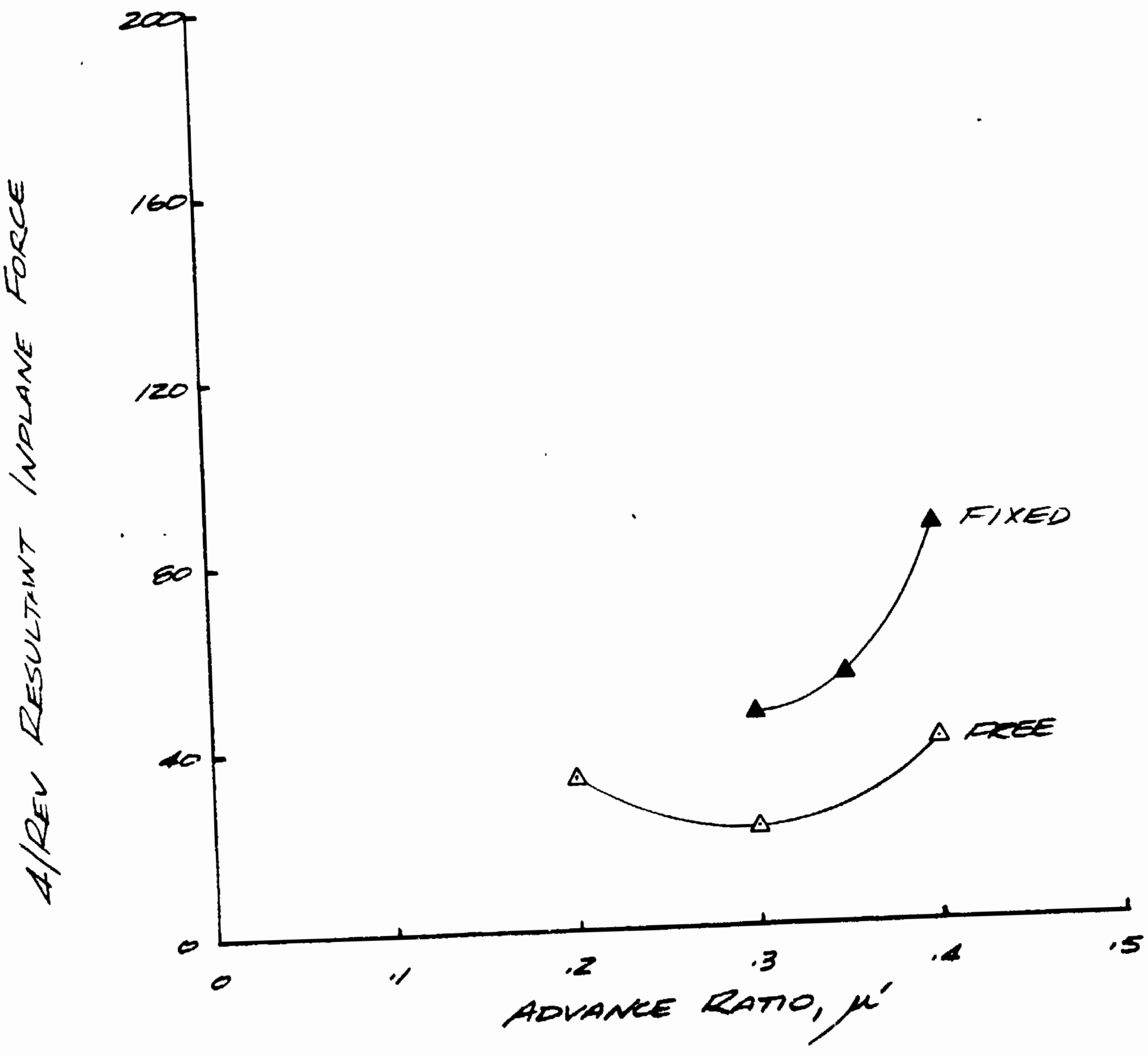
BVWT 271 CONSTANT LIFT TIP

△ TIP FREE MID WEIGHT
▲ TIP FIXED

$C_T/\sigma = .08$
$X/qD^2\sigma = 0$



KMB 10/8/81

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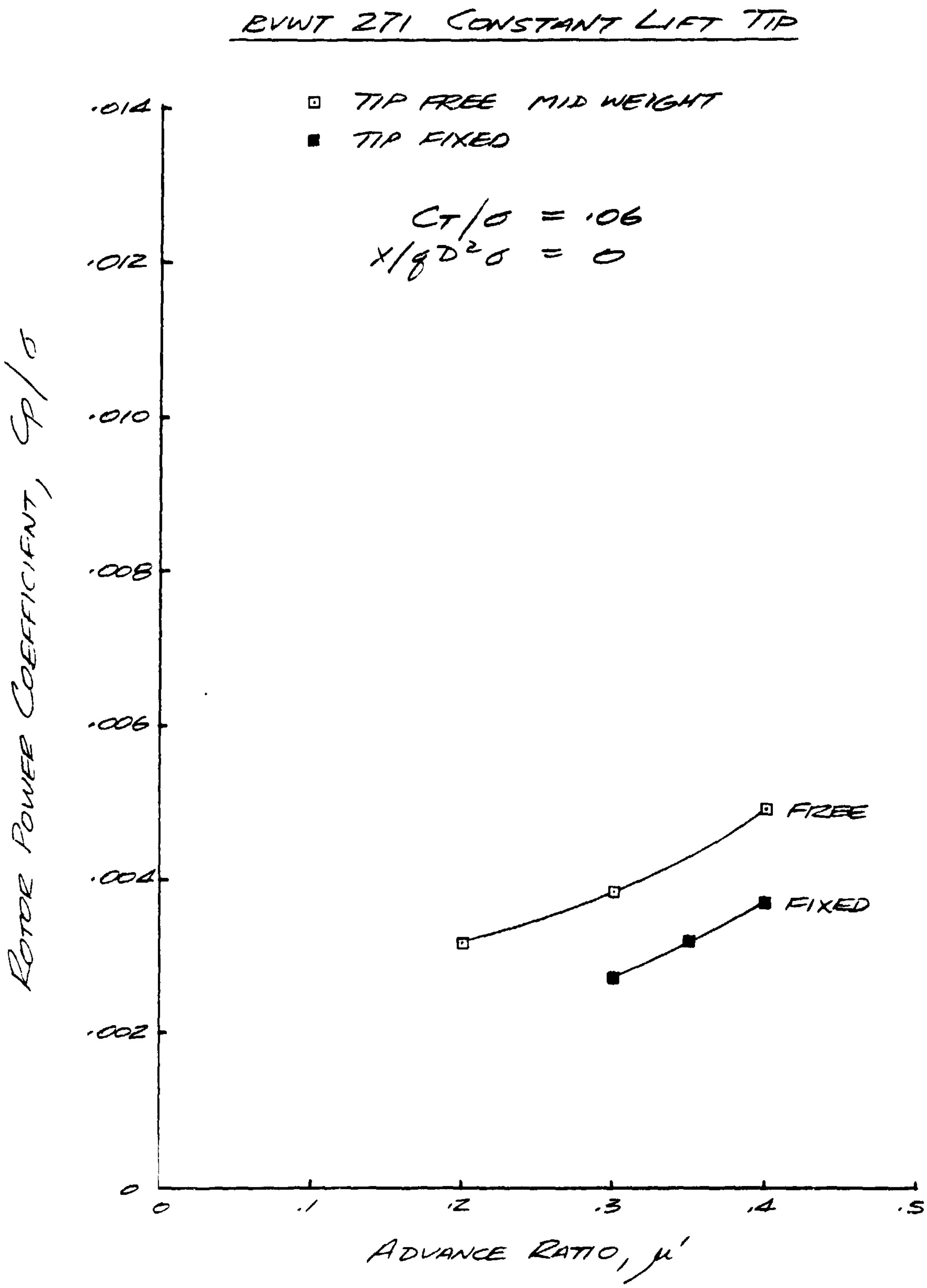
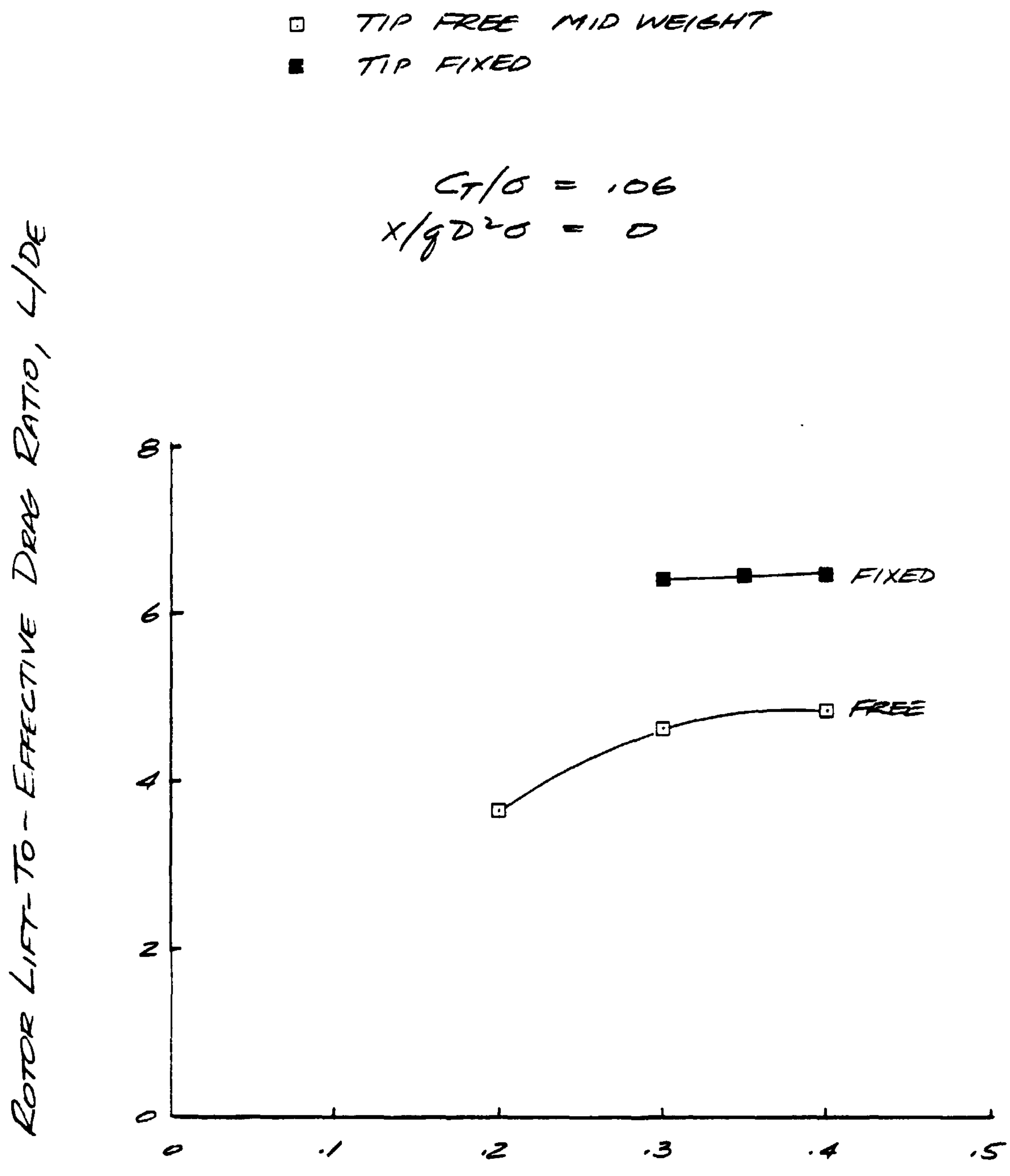


KMB 10/8/81

BVWT 271 CONSTANT LIFT TIP



KM13 10/8/81

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BVWT 271 CONSTANT LIFT TIP

□ TIP FREE MID WEIGHT

■ TIP FIXED

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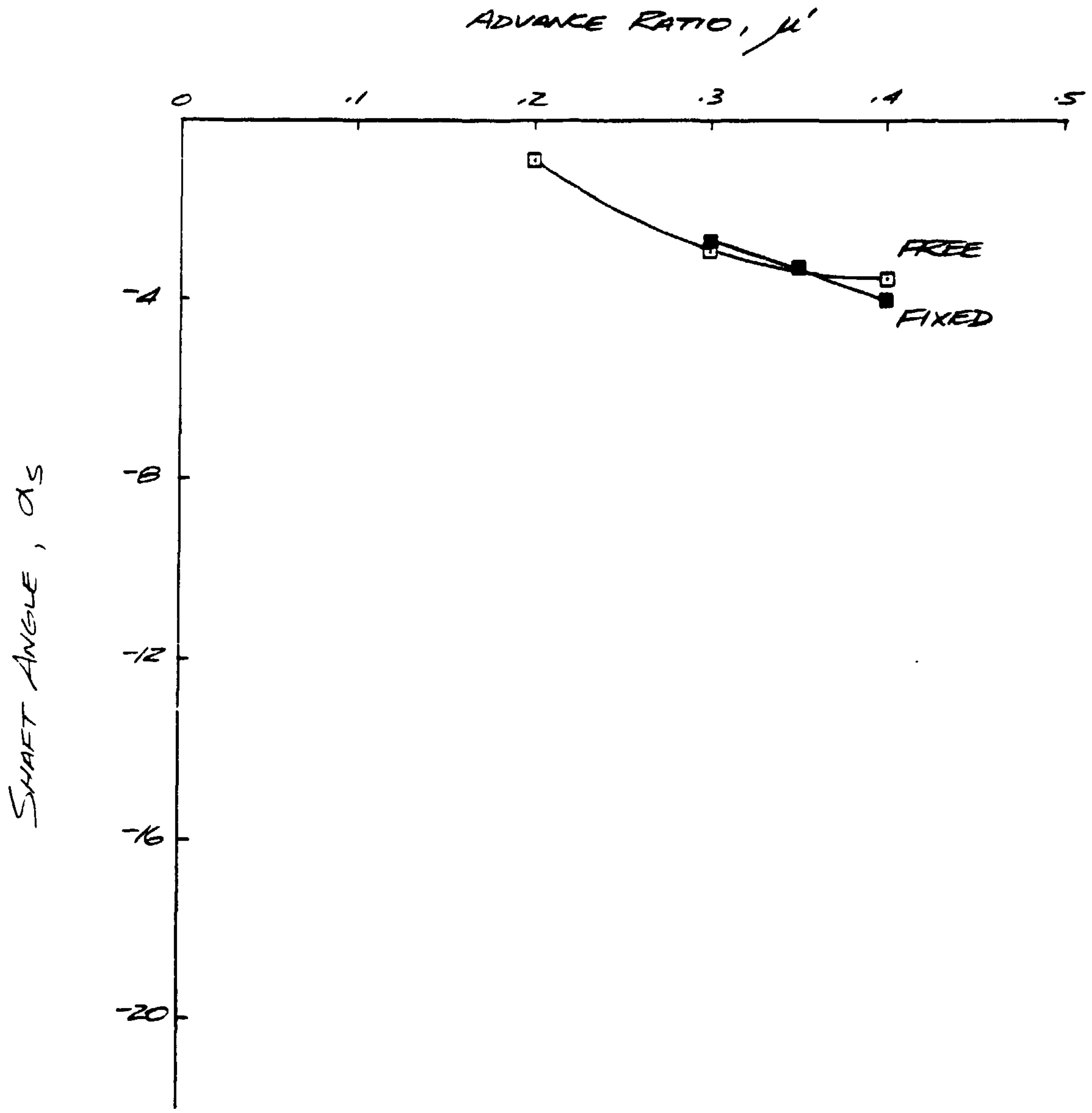
$X/qD^2\sigma = 0$

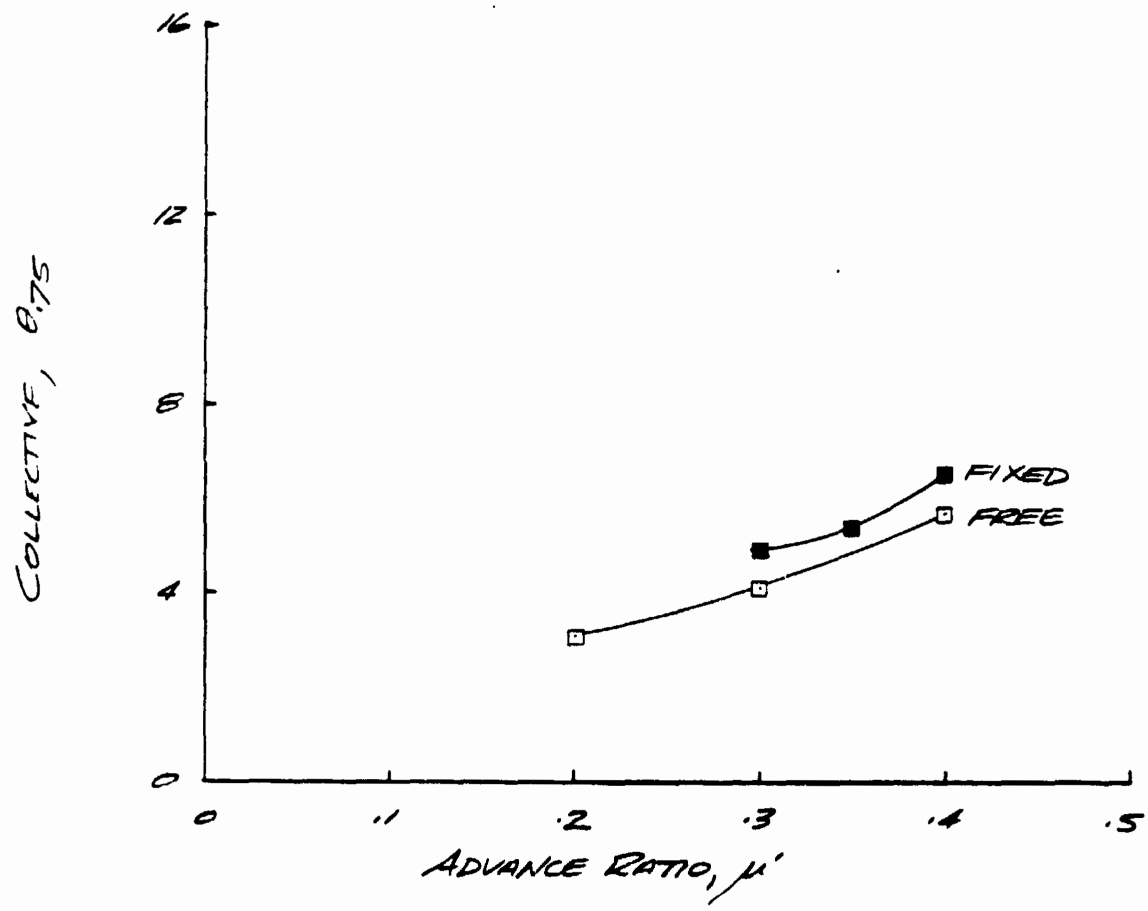


KMB 10/8/81

BVWT 271 CONSTANT LIFT TIP

□ TIP FREE MID WEIGHT
■ TIP FIXED

$C_T/\sigma = .06$
$X/qD^2\sigma = 0$

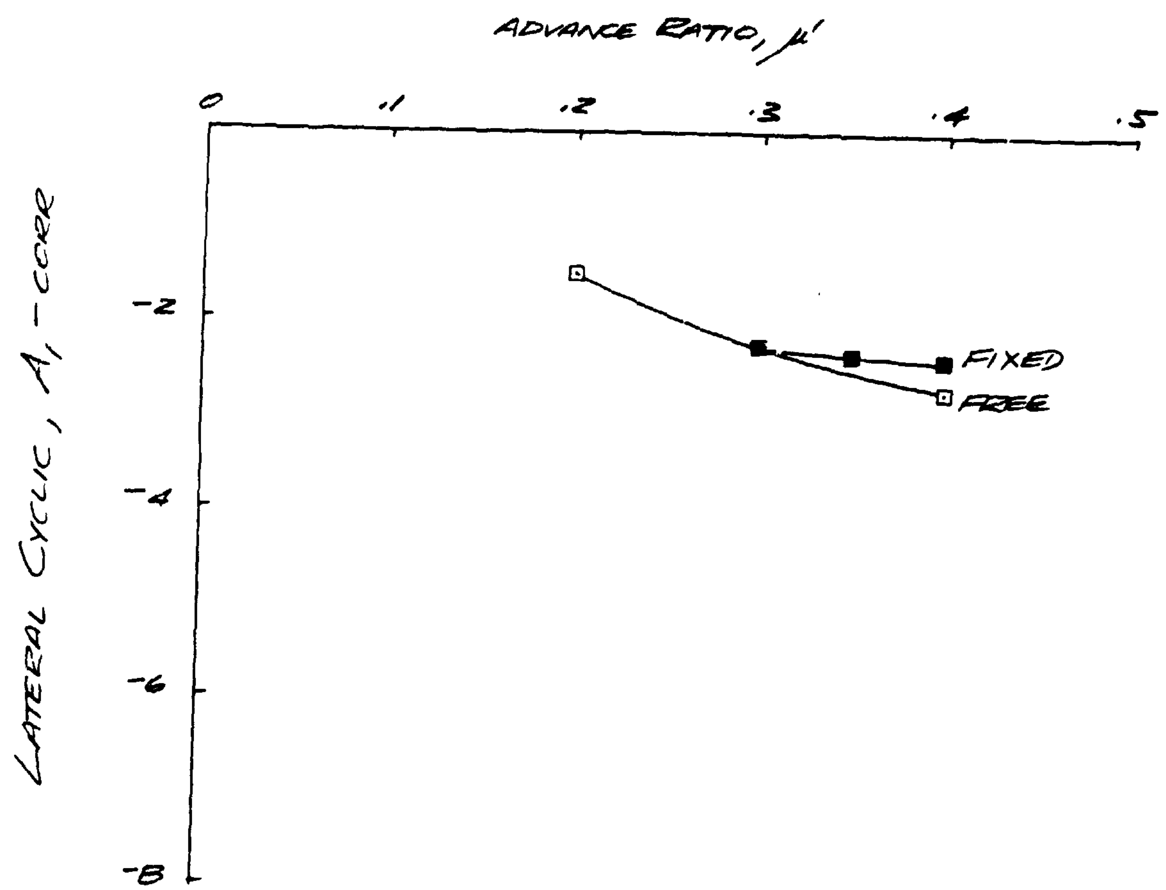


KMB 10/8/81

BVWT 271 CONSTANT LIFT TIP

□ TIP FREE MID WEIGHT
■ TIP FIXED

$C_T/\sigma = .06$
$X/qD^2\sigma = 0$



KMB 10/8/81

BVWT 271 CONSTANT LIFT TIP

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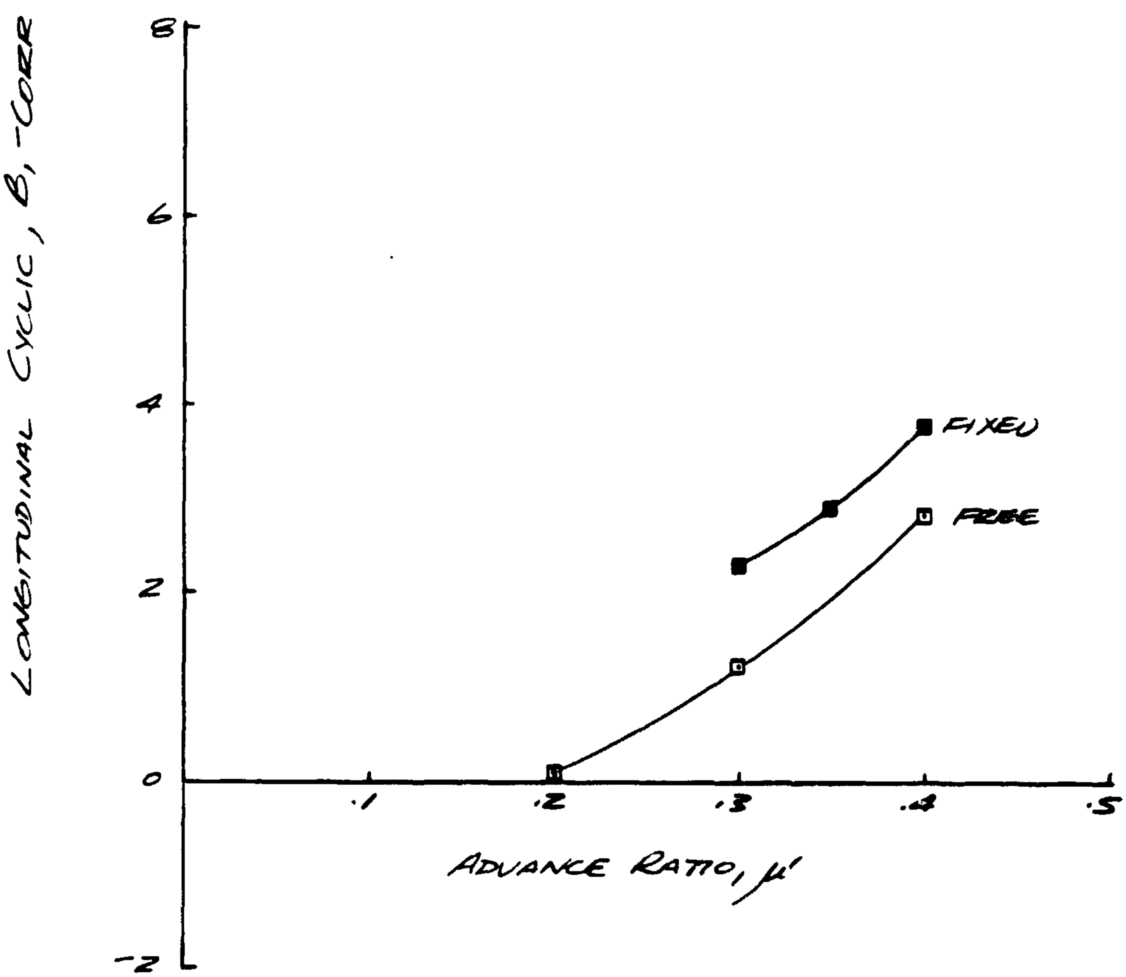
■ TIP FIXED

$C_T/\sigma = .06$
$X/qD^2\sigma = 0$



KMO 10/4/81

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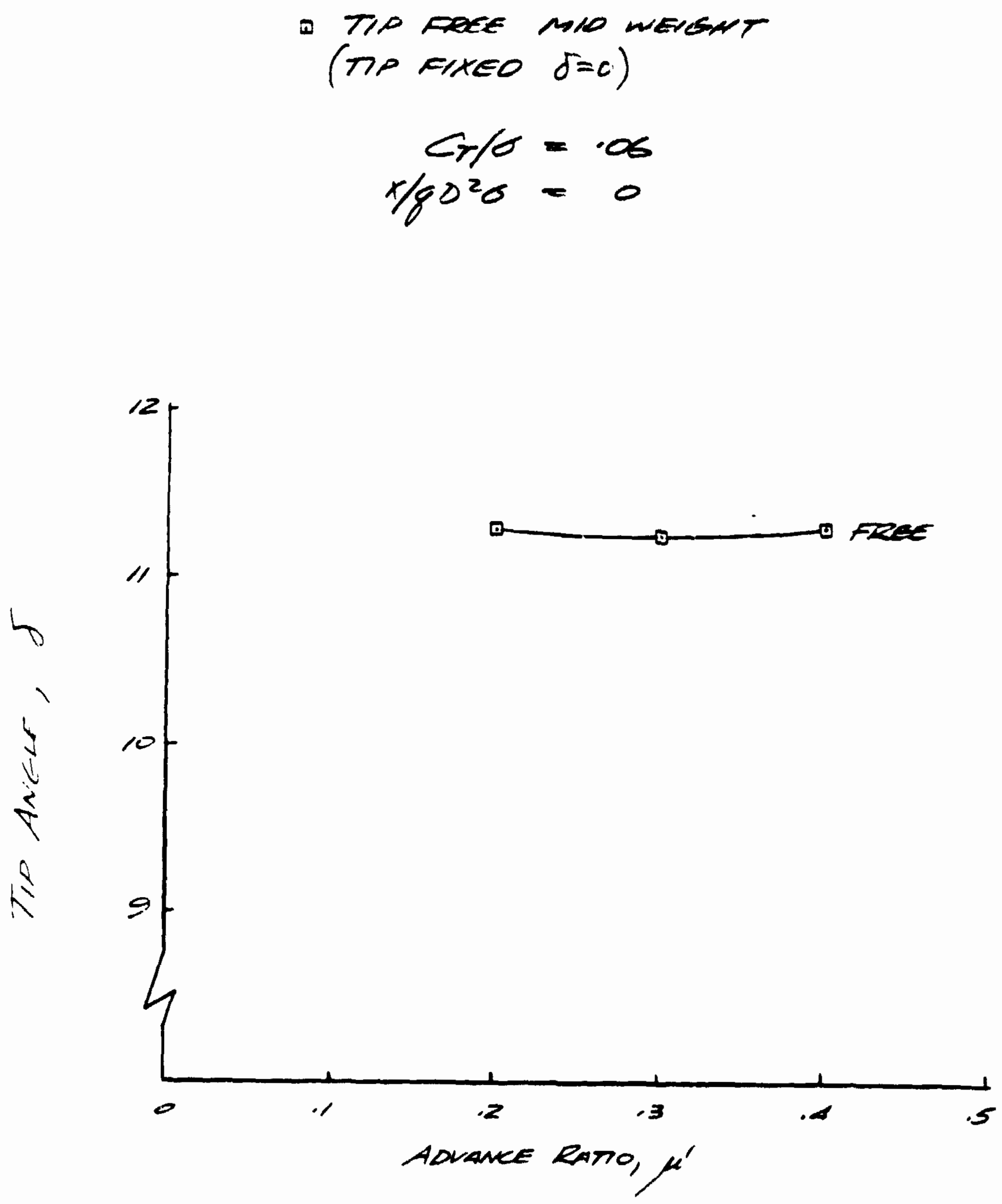

KMB 10/8/81

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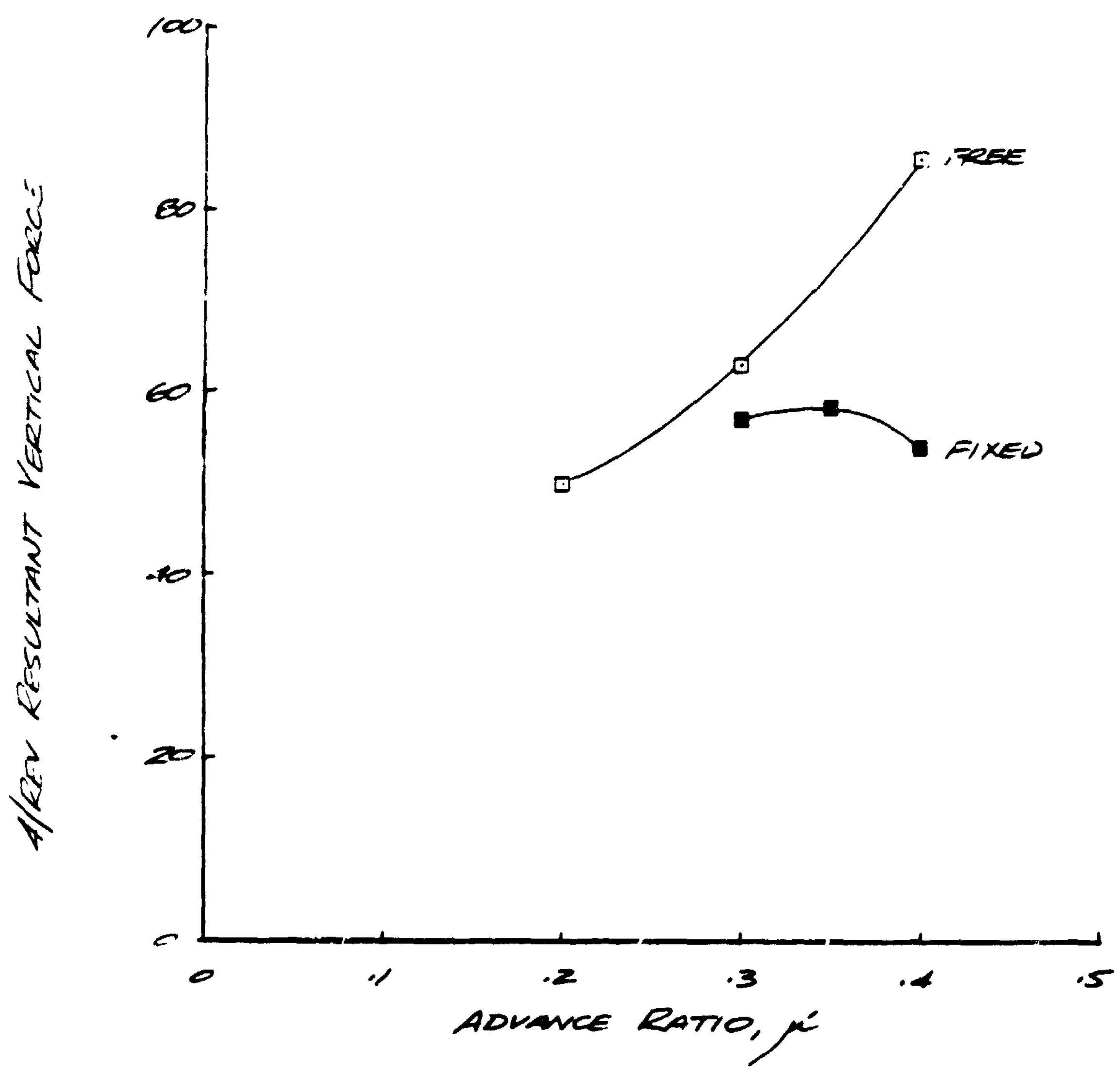
EVWT 271 CONSTANT LIFT TIP

□ TIP FREE MID WEIGHT

■ TIP FIXED

$C_T/\sigma = .06$

$X/q D^2 \sigma = 0$



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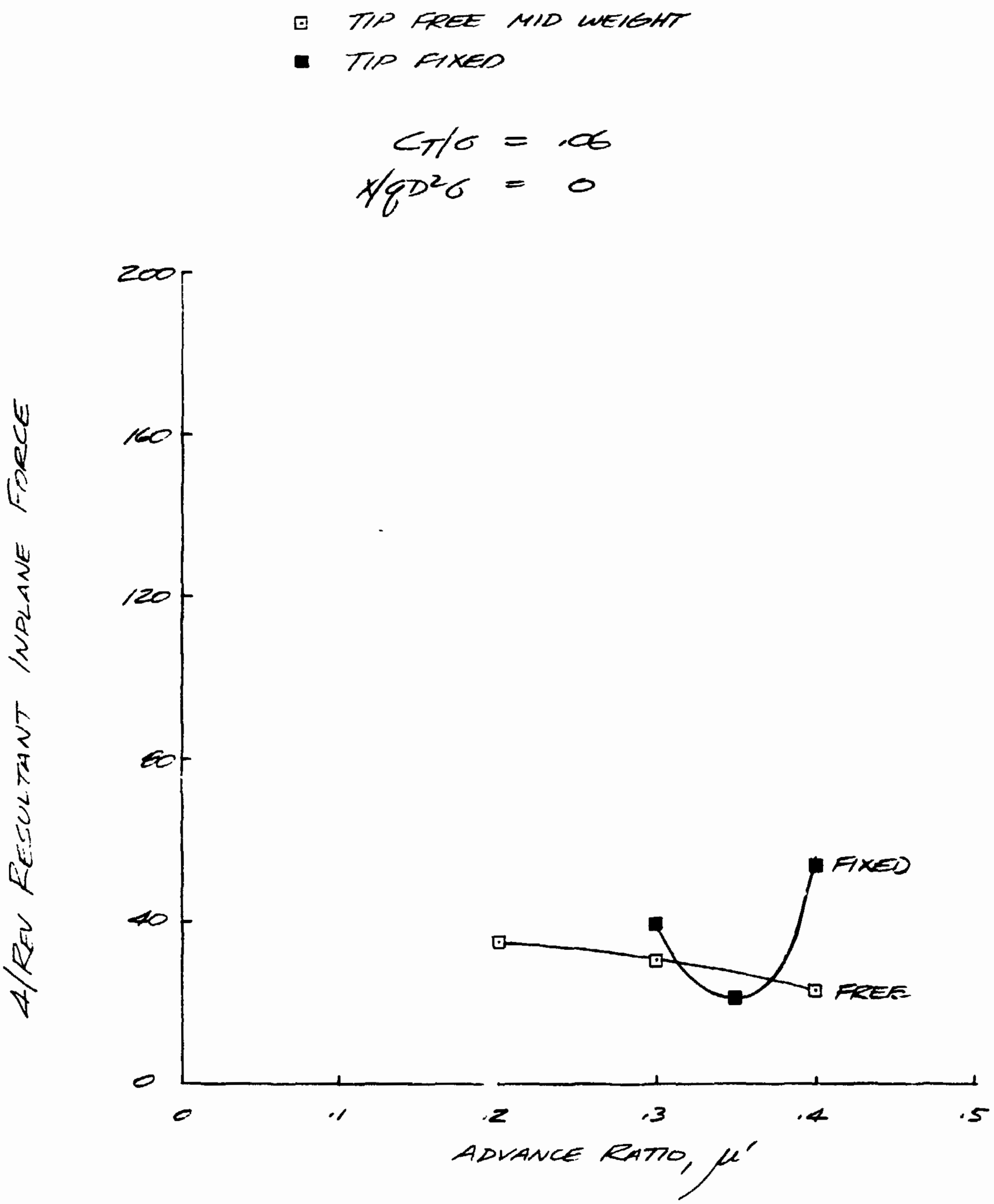
BVWT 271 CONSTANT LIFT TIP



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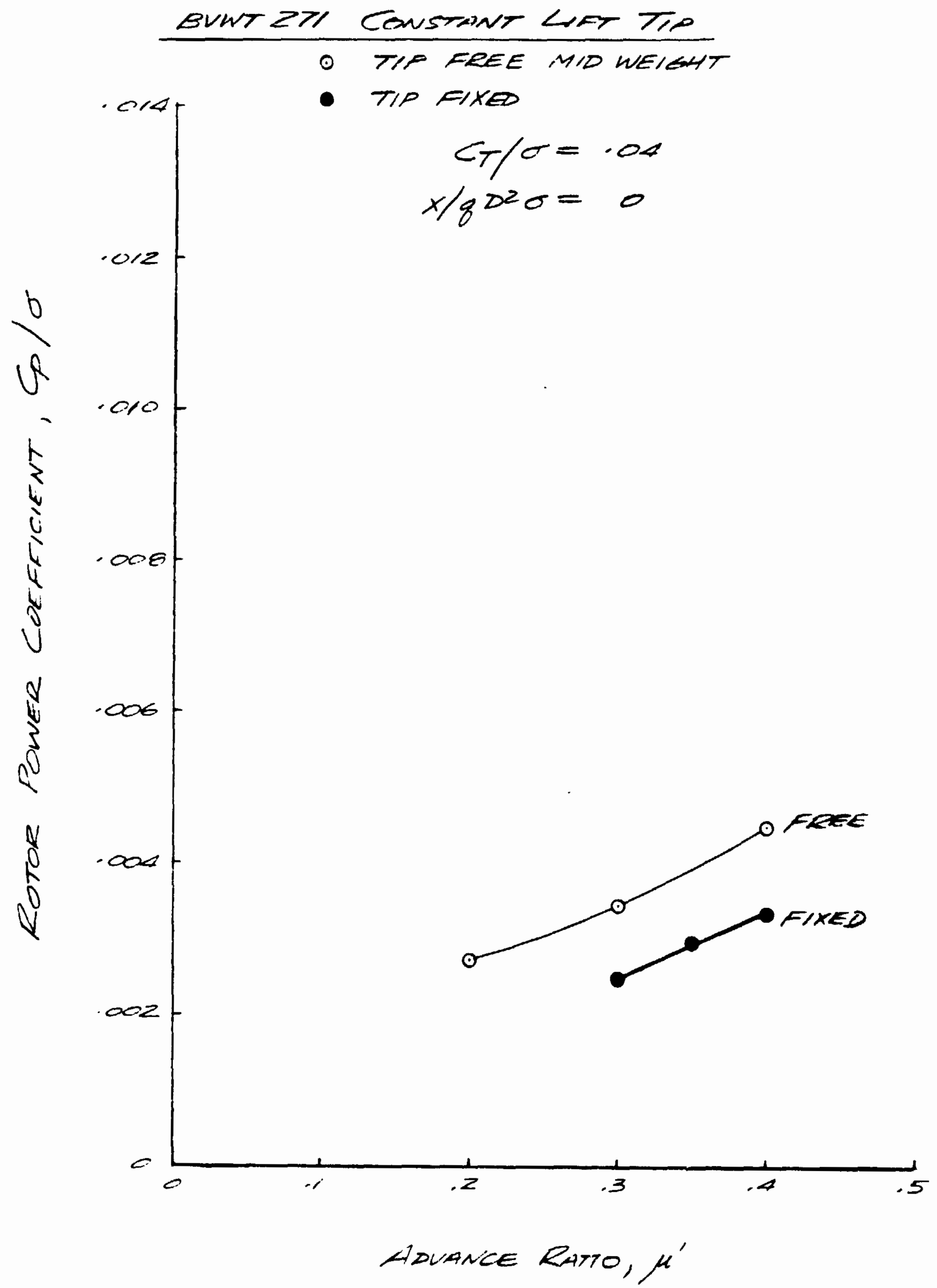

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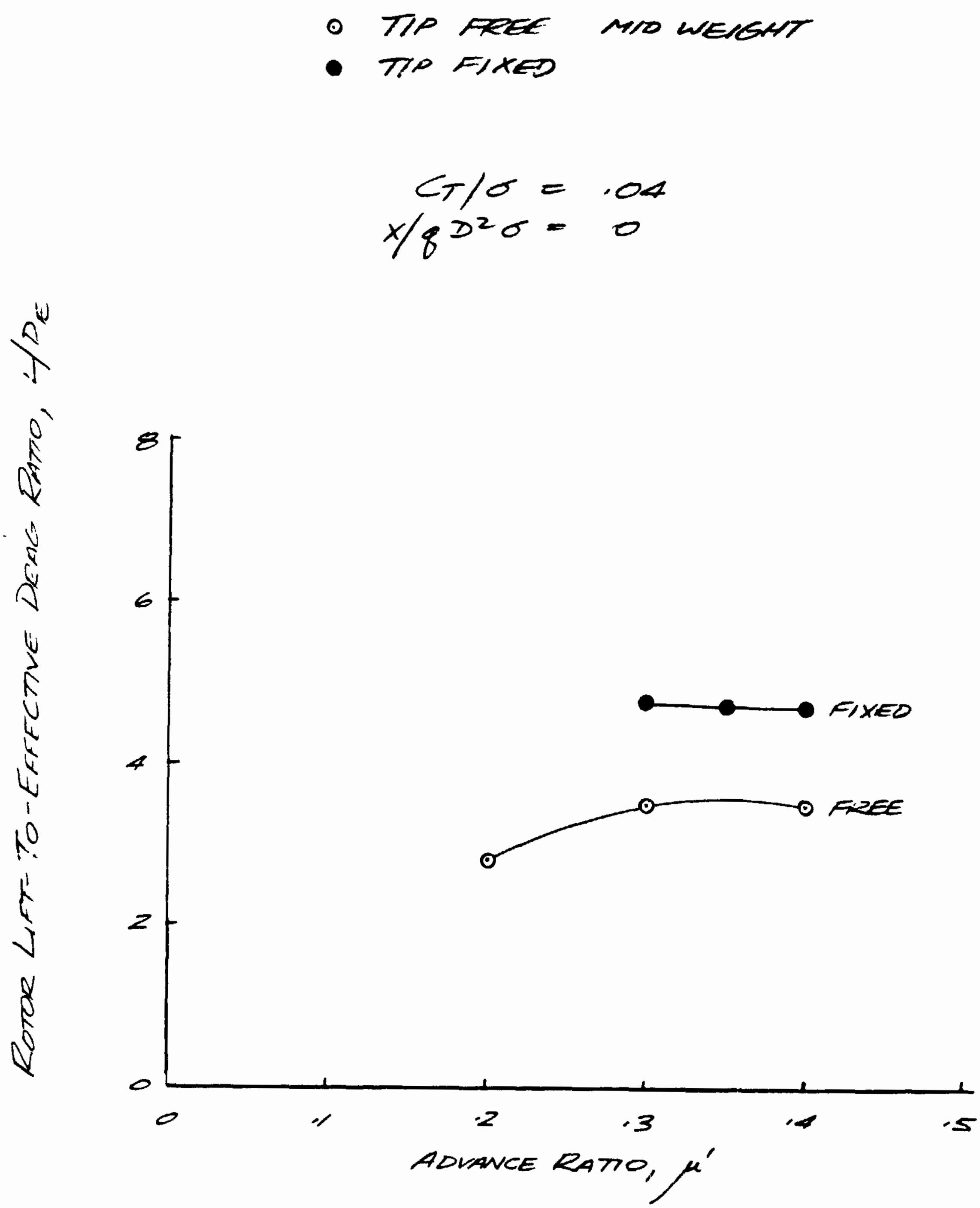
BVWT 271 CONSTANT LIFT TIP



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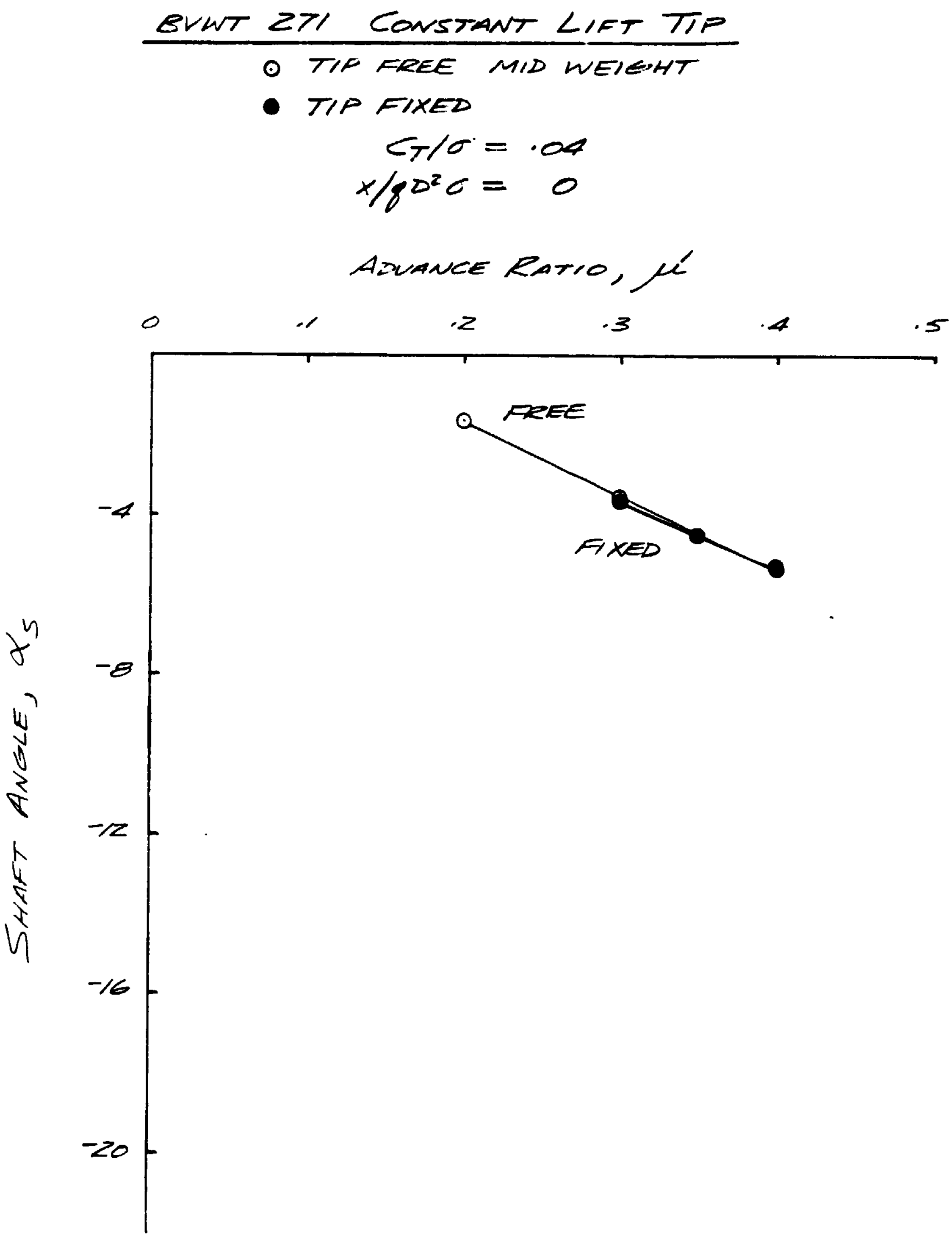
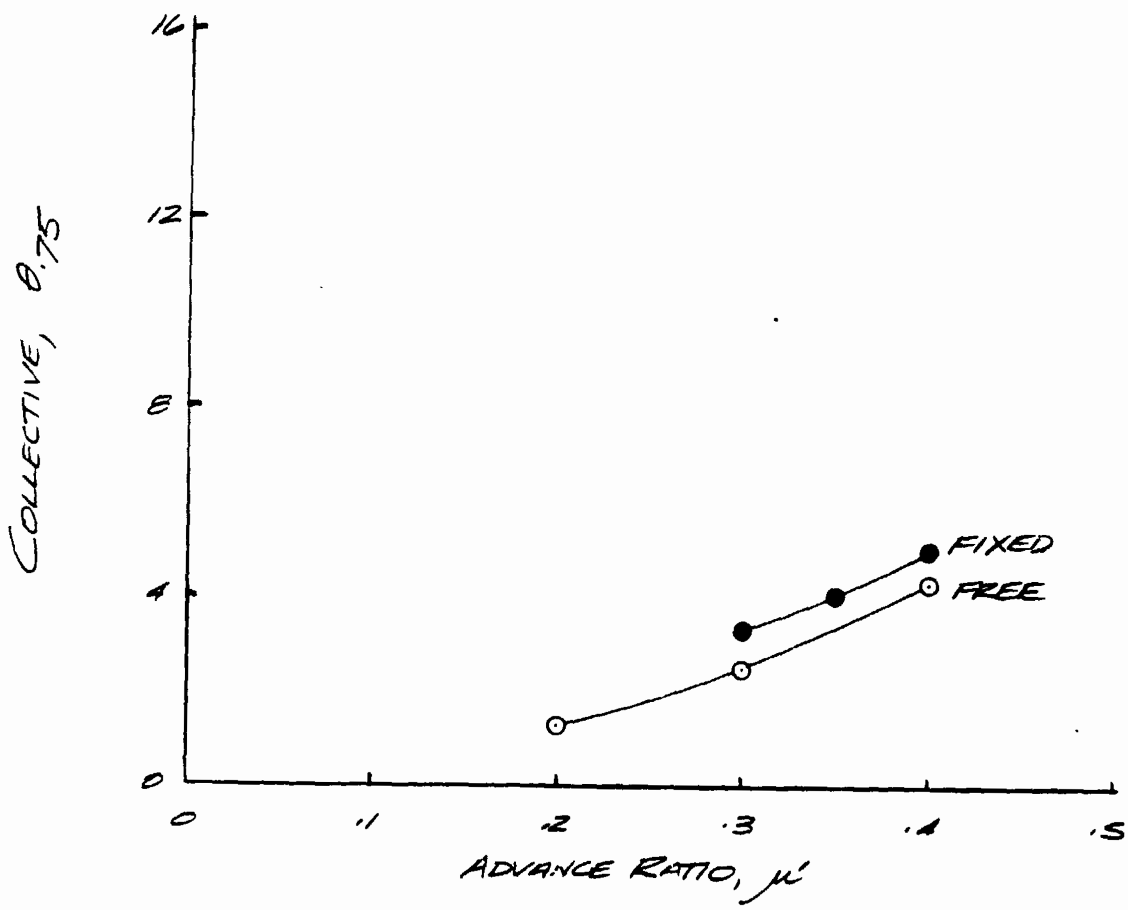

BVWT 271 CONSTANT LIFT TIP
TIP FREE MID WEIGHT
TIP FIXED
$C_T/\sigma = .04$
$X/qD^2\sigma = 0$
ADVANCE RATIO, μ
0
.1
.2
.3
.4
.5
FREE
FIXED
-4
-8
-12
-16
-20
SHAFT ANGLE, α_S

KMB 10/8/61

BVWT 271 CONSTANT LIFT TIP

⊙ TIP FREE MID WEIGHT
● TIP FIXED

$C_T/\sigma = .04$
$X/qD^2\sigma = 0$



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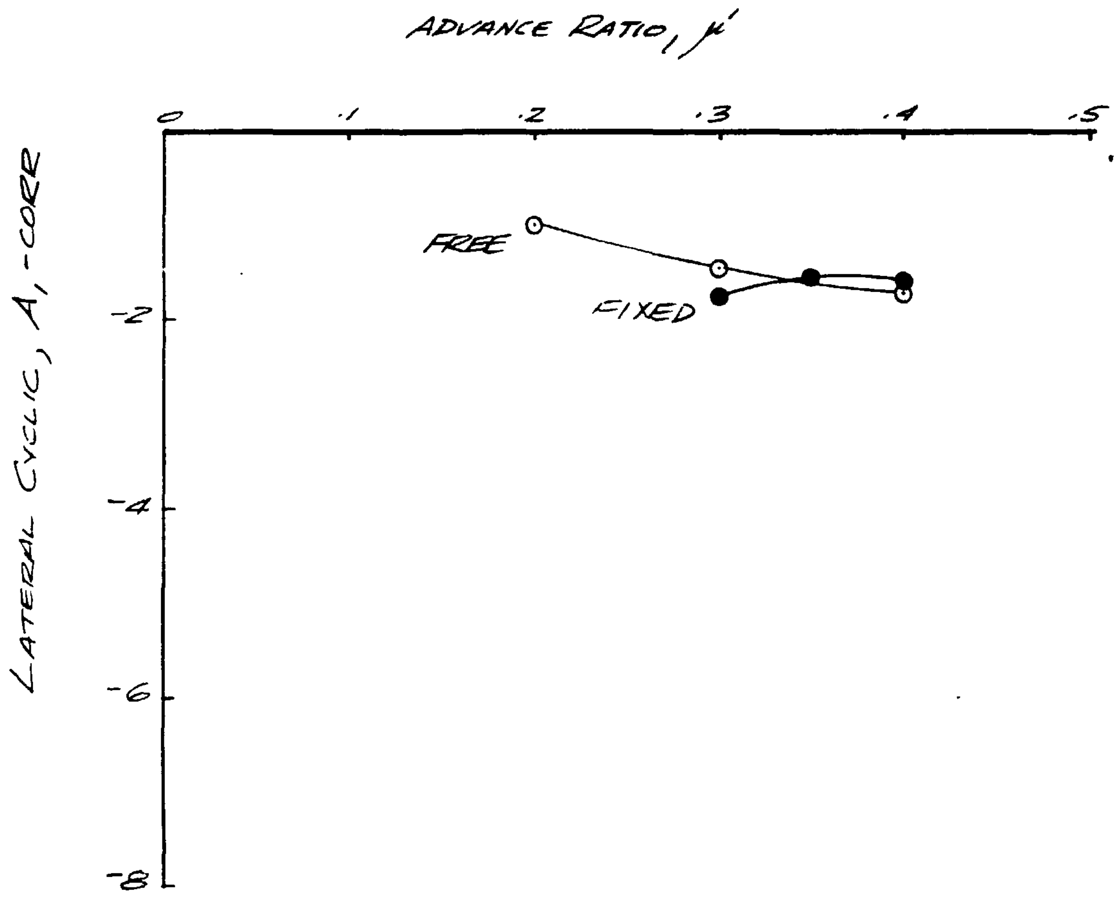
BVWT 271 CONSTANT LIFT TIP

○ TIP FREE MID WEIGHT

● TIP FIXED

$C_T/\sigma = .04$

$X/qD^2\sigma = 0$



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ORIGINAL PAGE IS
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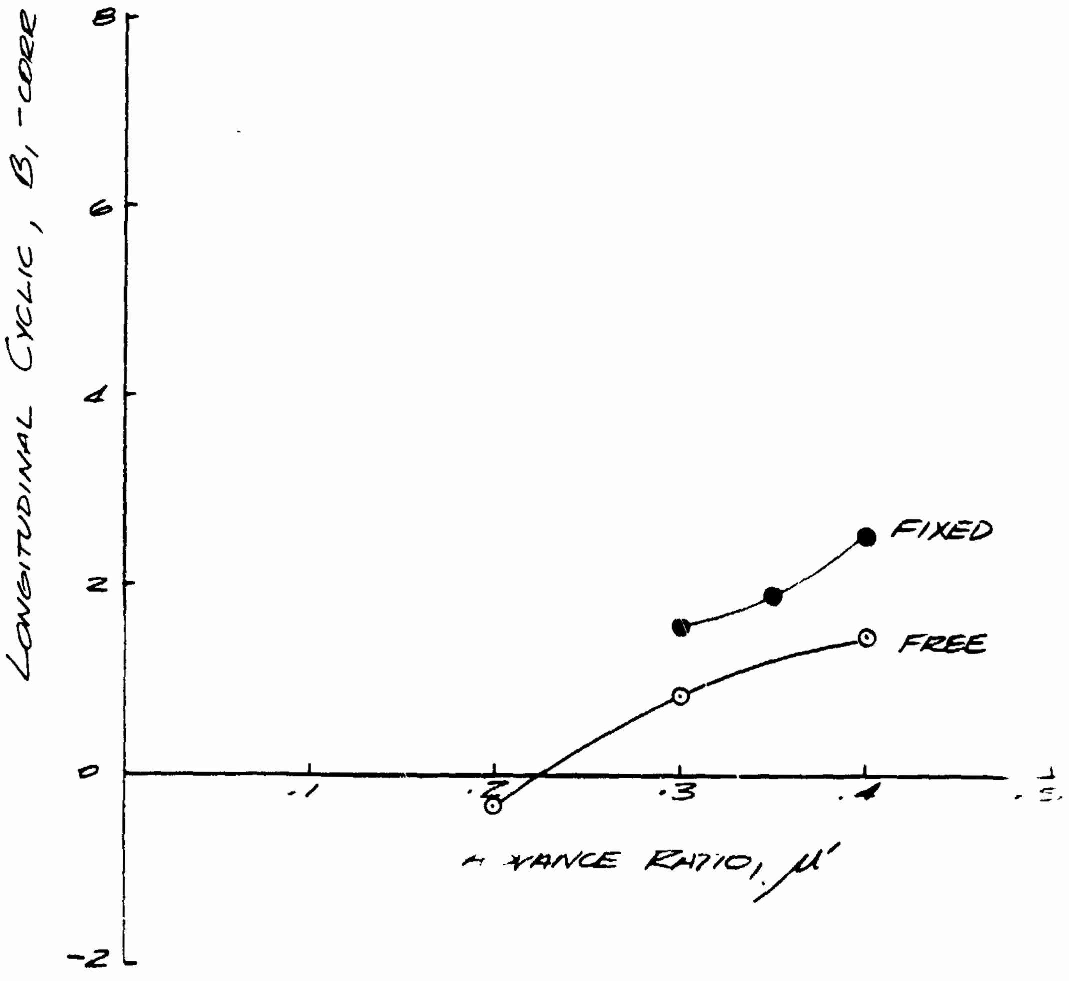
BVWT 271 CONSTANT LIFT TIP

⊙ TIP FREE MID WEIGHT
● TIP FIXED

$C_T/\sigma = .04$
$X/qD^2\sigma = 0$



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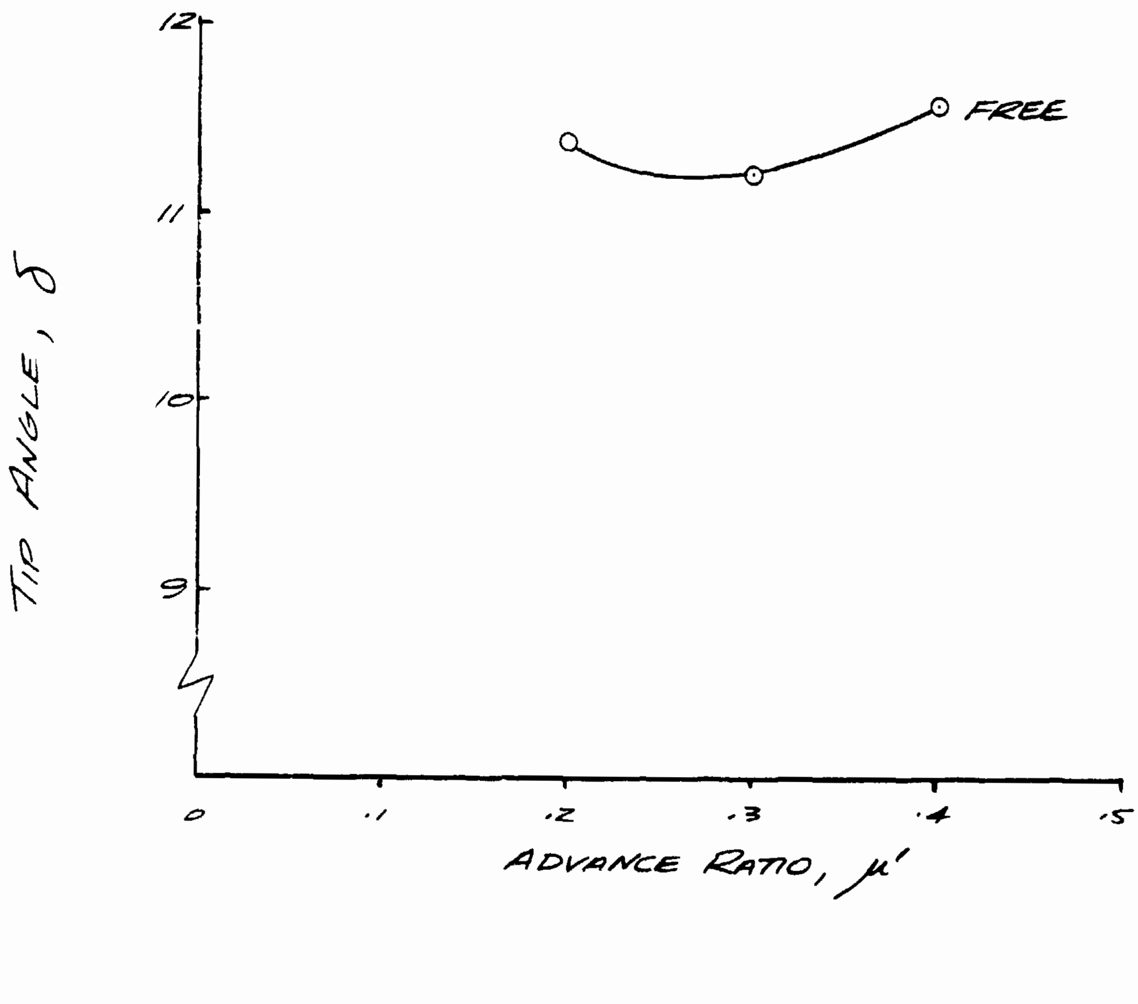
BVWT 271 CONSTANT LIFT TIP

⊙ TIP FREE MID WEIGHT
(TIP FIXED $\delta = 0$)

$C_T/\sigma = .04$
$X/qD^2\sigma = 0$



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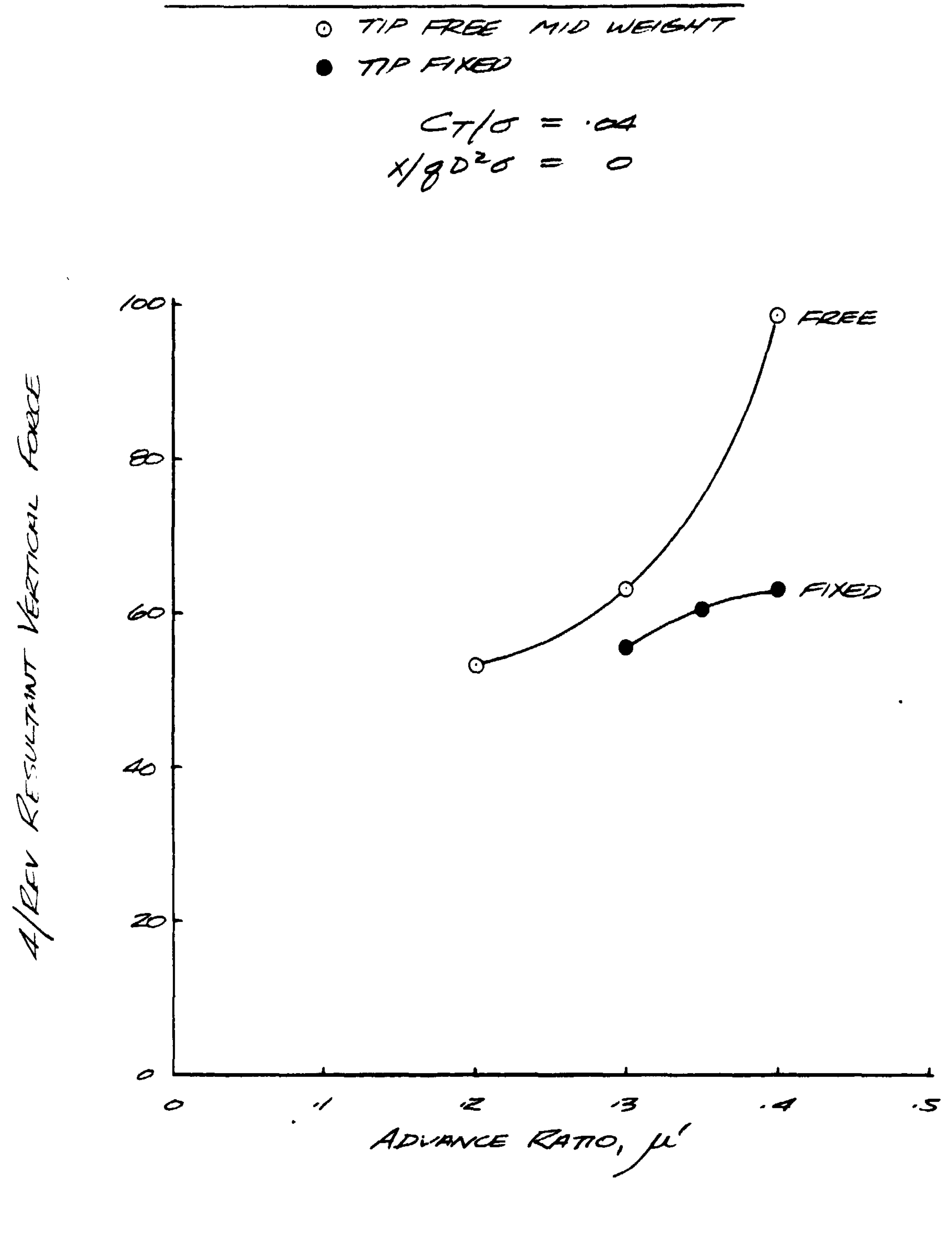
BVWT 271 CONSTANT LIFT TIP



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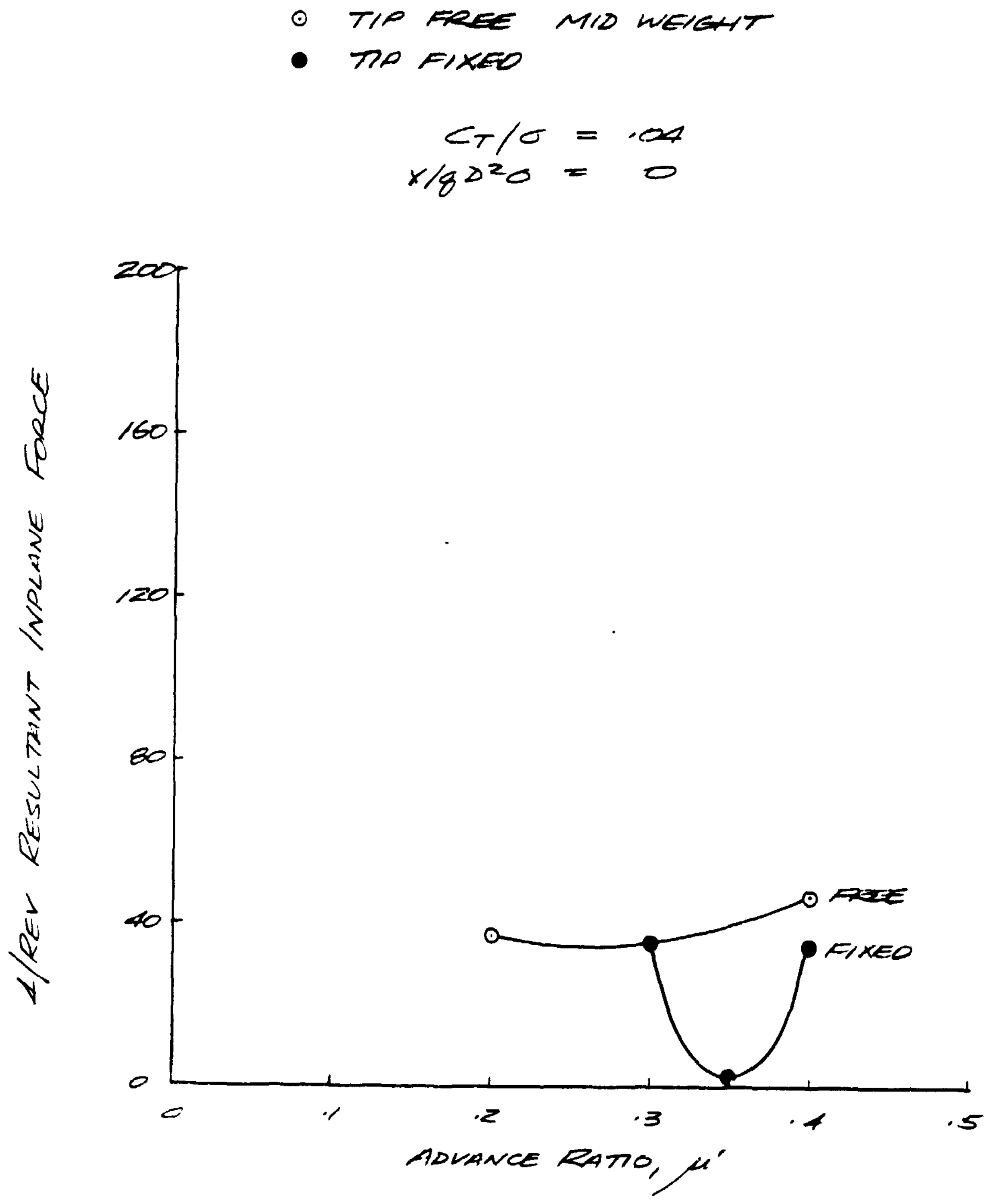
BVWT 271 CONSTANT LIFT TIP



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